Optimization of Slow Sand Filtration Design by Understanding the Influence of Operating Variables on the Suspended Solids Removal

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Zusammenfassung

Im Jahr 2015 bezogen weltweit etwa 663 Millionen Menschen ihr Trinkwasser aus unzureichend geschützten Quellen. Gleichzeitig haben es sich die Vereinten Nationen zum Ziel gesetzt, bis 2030 das universelle Recht auf sichere und bezahlbare Trinkwasserversorgung für jeden Menschen zu gewährleisten. Dieses Ziel kann durch die Installation von Technologien zur Wasserbehandlung erreicht werden, welche die Wasserqualität verbessern. Unter Berücksichtigung der für Entwicklungsländer relevanten Kriterien könnte Langsamsandfiltration eine geeignete Behandlungstechnologie zur Verbesserung der Wasserqualität sein.

Verschiedene Autoren geben Empfehlungen zum Bau wirksamer Langsamsandfilter. Als entscheidende Parameter für die Ausführung der Filter wurden die Korngrößenverteilung des Filtersandes sowie die hydraulische Belastungsrate identifiziert. Entsprechend der gängigen Empfehlungen sollte das Filtermedium feinkörnig (d_{10} 0.15-0.35 mm/C_u < 3) und die Belastungsrate niedrig genug (0.04 – 0.40 m/h) sein, um einen hohen Reinigungsgrad zu erreichen. Dabei ist zu berücksichtigen, dass auch bei diesen Konfigurationen kein bakterien- und virenfreies Filtrat garantiert werden kann. Ein weiterer Behandlungsschritt zu Desinfektion wird immer benötigt, um die übrigen Mikroorganismen zu entfernen und das Filtrat als Trinkwasser nutzbar zu machen. Bei niedrigen Belastungsraten wird allerdings eine große Filterfläche benötigt. Aufgrund dieser Einschränkung sank die Beliebtheit von Langsamsandfiltern Anfang des 20. Jahrhunderts. Deshalb wird eine Optimierung der empfohlenen Auslegungskriterien von Langsamsandfiltern benötigt, wodurch diese Einschränkung aufgehoben werden kann. Es mangelt derzeit weiterhin an einer Beschreibung des grundlegenden Entfernungsmechanismus durch Langsamsandfiltration, was die breitere Anwendung dieser Technologie weiter einschränkt.

Das Hauptziel dieser Arbeit ist die Optimierung der empfohlenen Entwurfskriterien von Langsamsandfiltern als Wasseraufbereitungstechnologie. Im Mittelpunkt stand der Korngrößenverteilung des Filtermediums, ausgedrückt als effektive Größe d_{10} und Ungleichförmigkeitsgrad C_u, sowie der hydraulischen Belastungsrate auf die Reinigungsleistung von Schwebstoffen. Der hier verfolgte Ansatz liegt in der unabhängigen Betrachtung aller Kenngrößen, die auf den Wirkungsgrad des Filters Einfluss nehmen. Die experimentelle Arbeit wurde in zwei Phasen unterteilt. In der ersten Phase lag der Fokus auf der Identifikation der operativen Kenngrößen, die einen Einfluss auf die Partikelentfernung haben. Dazu wurden 18 Filtersäulen mit verschiedenen Filterkonfigurationen gebaut. In der zweiten Phase lag der Fokus auf dem Einfluss der Parameter auf die Eindringtiefe der Feststoffe in den Filter. Dabei wurde auch der Einfluss einer Schutzschicht auf die Filterlaufzeit evaluiert. Insgesamt wurden in der zweiten Phase 13 Filtersäulen getestet.

Die Ergebnisse zeigen, dass die bisherigen Empfehlungen der Parameter eher konservativ ausgelegt sind. Bei der Verwendung von gröberem Filtersand (d_{10} 0.90 mm und C_u 2.5) wird immer noch eine durchschnittliche Ablauftrübung von unter 1 NTU erreicht. Es konnte weiterhin gezeigt werden, dass der Betrieb der Filter bei höheren Belastungsraten von 0.80 m/h nicht zu einer höheren Trübung im Ablauf führt. Basierend auf diesen Ergebnissen wurden neue Empfehlungen für Entwurfskriterien festgelegt, bei denen die Spanne der verwendbaren Korngrößenverteilungen und der hydraulischen Belastungsrate vergrößert wurde. Diese umfasst eine d_{10} von 0,25 – 0,50 mm und C_u von 2.5 – 7 mit einer hydraulischen Belastungsrate von 0,20 – 0,60 m/h. Höhere hydraulische Belastungsraten von 0,60 – 0,80 m/h können für feinen Filtersand mit d_{10} von 0,25 mm und $C_u < 3$ angewendet werden. Gröberer Filtersand (d_{10} 0,50 – 0,90 mm/$C_u < 3$) kann als Alternative bei einer hydraulischen Belastungsrate ≤ 0,40 m/h verwendet werden. Die Aufbringung einer Schutzschicht aus Kies verlangsamte die Abnahme der Filterkapazität durch die Siebwirkung um bis zu 70 %.

Weitere Empfehlungen wurden für einen Langsamsandfilter in Gunungkidul auf Java, Indonesien getroffen. Wegen der dortigen niedrigen Belastungsraten von 4 m/d und begrenztem Platzangebot konnte eine bereits existierende Pilotanlage nicht den Bedarf von fünf Dörfern mit insgesamt etwa 2800 Einwohnern decken. Unter den hier vorgestellten Richtlinien könnte mit gröberem Filtermaterial die Belastungsrate bei gleicher Reinigungsleistung verdoppelt werden, ohne die Betriebskosten oder die beanspruchte Fläche zu erhöhen. Dies ist ein Beleg dafür, dass Langsamsandfiltration ein großes Potential hat, die Trinkwasserversorgung speziell in Entwicklungsländern zu verbessern.

Schlagworte: Langsamsandfiltration, Entfernungsmechanismus, Trinkwasseraufbereitung, Filterkapazität, hydraulische Belastungsrate

Abstract

In 2015, 663 million of people who mostly live in the developing countries were still consuming unimproved water sources. On the other hand, United Nations set-up a target that by 2030, a universal and equitable access for safe and affordable drinking water for everyone must be achieved. This target can be achieved by implementing a water treatment technology to improve water quality for the community. By considering the terms 'safe', 'affordable' and 'developing countries', slow sand filtration can be the suitable treatment technology to improve water quality.

In order to construct an effective slow sand filter, some recommendations on the design criteria have been proposed by several authors. Two critical parameters for the design criteria are the grain size distribution and the hydraulic loading rate. According to the recommendation, the filter media should be fine i.e. d_{10} 0.15-0.35 mm/C_u < 3 and the rate should be low enough i.e. 0.04 – 0.40 m/h to ensure its removal efficiency. In fact, even though the slow sand filter is constructed using fine media and operated under low hydraulic loading rate, it cannot be guaranteed that the filtrate is bacteria and viruses free. A further step of treatments such as disinfection is always needed to remove the microorganisms left after filtration so that the water can be used for drinking water purposes. As a consequence of these low loading rates, a large filter area is needed. Due to this limitation, in the early 20th century, slow sand filter became less attractive. Therefore, an optimization on the recommended design criteria of slow sand filtration is required to overcome this limit. Unfortunately, a comprehensive description on the fundamental removal mechanism of slow sand filtration is still missing inhibiting the optimization and wider application of this technology.

The main purpose of this work is to optimize the design recommendation of slow sand filtration as a technology to improve the water quality. In order to achieve this purpose, a specific objective is defined i.e. to understand the influence of the grain size distribution of filter media represented by effective size d_{10} and uniformity coefficient C_u and the hydraulic loading rate on the removal mechanisms of suspended solids. The approach to reach this objective is by investigating each operating variable independently so that its influence on the filter performance can be compared equally. The main experimental work was divided into two phases. In the Phase I, the focus was to identify the influence of operating variables on the suspended solids removal. A total of 18 filter columns with different filter configuration were constructed for the investigation in Phase I. The focus in Phase II was to find out the influence of the operating variables on the solids penetration in filter depth including the evaluation on the method to prolong the filter run time by applying protection layer. For the Phase II, a total of 13 filter columns were tested.

The results of this study showed that the recommended values of operating variables are rather conservative. By using coarse media represented by d_{10} of 0.90 mm and C_u of 2.5, an average outlet turbidity of less than 1 NTU could still be obtained. In regard to the hydraulic loading rate, it was also found that operating the filter at high rate up to 0.80 m/h did not deteriorate the filter efficiency significantly. Hence, based on these results, a new recommendation of the design criteria, where the usable range of the grain size distributions of the filter media and hydraulic loading rate is expanded, has been proposed. The new range proposed for filter media is d_{10} 0.25 – 0.50 mm/C_u 2.5 – 7 with the hydraulic loading rate of 0.20 – 0.60 m/h. Higher hydraulic loading rate of 0.60 – 0.80 m/h can be applied for fine sand with d_{10} of around 0.25 mm and $C_u < 3$. Coarser sand (d_{10} 0.50 – 0.90 mm/C_u <3) can also be alternatives with the hydraulic loading rate of ≤ 0.40 m/h. Based on the evaluation of the method to prolong the filter run time, it was found that applying gravel as a protection layer could be a promising method to decelerate the decrease of filter capacity by up to 70 % by acting as strainer.

A recommendation was also given for the slow sand filter constructed in Gunungkidul in Java Island, Indonesia. Due to low loading rate of 4 m/d and limited space, an existing pilot plant was not able to comply with the water demand of five sub-villages (around 2,800 inhabitants). Following the new design recommendations proposed in this study, the hydraulic loading rate of the system could be doubled by using coarser filter material, while maintaining the operating costs, filter area and high suspended solids removal capacity. This shows that slow sand filtration has a great potential to improve drinking water security especially in developing countries.

Keywords: slow sand filtration, water treatment, suspended solids removal mechanism, design optimization, drinking water quality, hydraulic loading rate, filter media

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List of Abbreviations

ANOVA	Analysis of Varian
BOD	Biochemical Oxygen Demand
EPA	Environmental Protection Agency
IWRM	Integrated Water Resources Management
NG	narrow graded sand
NTU	Nephelometric Turbidity Unit
PDAM	Perusahaan Daerah Air Minum (local water company in Indonesia)
PL	protection layer
TSS	Total Suspended Solid
UNICEF	United Nations Children's Fund
WG	wide graded sand
WHO	World Health Organization
WOPL	without protection layer
WPL	with protection layer

1 Introduction

The demand of water supply is directly proportional with the increase in global population. At the same time, water quality degradation causes the decrease in the amount of freshwater available for consumption (Peters and Meybeck, 2000). In 2015, it was reported that 663 million people worldwide were consuming unimproved water sources or surface water (United Nations, 2016). According to Unicef and WHO (2015), most of these people are living in sub-Saharan Africa and Asia (see Figure 1). Meanwhile, United Nations set-up several targets in the Agenda 2030 for Sustainable Development which one of them is *"by 2030, achieve universal and equitable access to safe and affordable drinking water for all"* (Assembly, 2015). In order to achieve the target, a suitable water treatment technology to improve the water quality must be implemented in these regions.

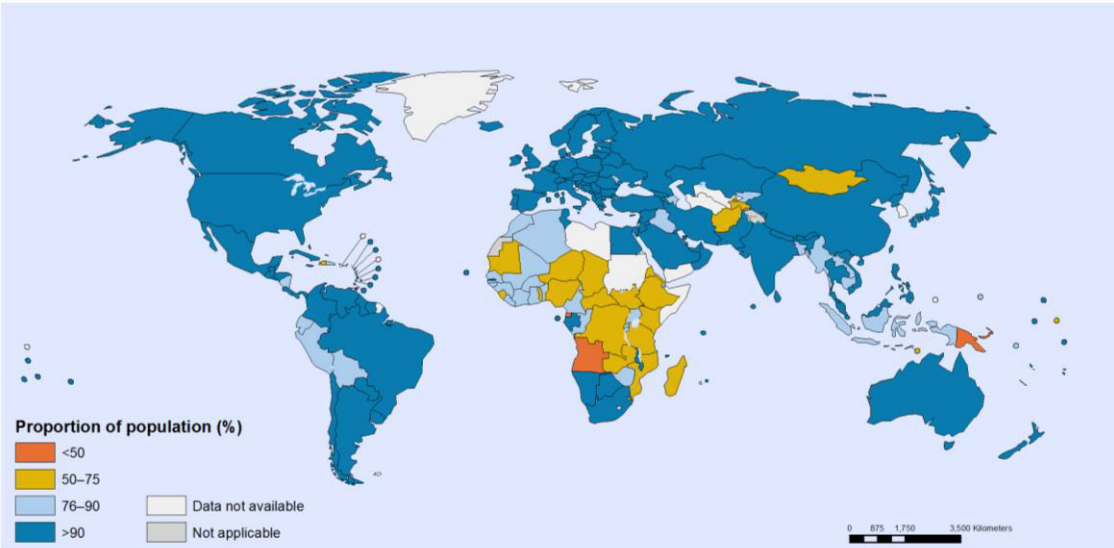


Figure 1. Proportion of population using improved drinking water source (Information Evidence and Research (IER) WHO, 2015)

Considering that most of the people are living in developing regions, treatment technologies to improve the water source must fulfill these criteria as follows (Duke *et al.*, 2006; Baker and Duke, 2006; Ray and Jain, 2011; Guchi, 2015):

a. simple to install, operate and maintain to comply with the local resources,

b. low capital, operation and maintenance cost considering the affordability and sustainability, and

c. effective to improve the water quality.

The water treatment concept which can meet those requirements is slow sand filtration (Baker and Duke, 2006; Silva, 2010; Ray and Jain, 2011; Fuchs *et al.*, 2015). Cleary (2005) stated that slow sand filtration is a suitable technology for small community. This statement confirmed that slow sand filtration is the best alternative for developing countries by considering that in the developing countries, many people still live in rural area which was divided into small community. Clark *et al.* (2012) stated that slow sand filter is a favorable technology for the developing countries because it barely uses chemicals, is simple to operate and maintain and is inexpensive.

Fuchs et al. (2015) conducted a study on the selection and installation of drinking water treatment in Indonesia, one of developing countries in Asia. In the study, Fuchs et al. compared four water treatment technologies: rapid sand filter, slow sand filter, diatomaceous earth filtration and membrane filtration. According to the evaluation which was based on the capability to meet regulatory requirements, capability to provide treatment technology with low cost and level of operation and maintenance, slow sand filter was found to be the most suitable technology for this region.

Slow sand filter may be considered as the oldest water treatment technology. The first documented slow sand filter was reported in 1804 when John Gibb constructed an experimental sand filter and implemented it successfully at his bleachery in Paisley, Scotland (Guchi, 2015). In 1829, this technology was adopted for a public water supply by James Simpson at the Chelsea Water Company in London for the first time (Barrett *et al.*, 1991). Since then, the use of slow sand filter for public purpose became well developed. According to Huisman and Wood (1974), Haig *et al.* (2011) and Gottinger *et al.* (2011), slow sand filter can provide settlement, straining, filtration, removal and inactivation of microorganisms, chemical change and even –under certain circumstances– storage in a single unit. However, the slow sand filtration alone will not be able to produce water which is free from bacteria and viruses (Bellamy *et al.*, 1985a; Bellamy *et al.*, 1985b; Collins *et al.*, 1991; Galvis, 1999). Therefore, further treatment such as disinfection is always needed.

In order to ensure its performance, it was recommended to use a fine media and the filter is designed to be operated at a very low hydraulic loading rate (Huisman and Wood, 1974). By following this recommendation without interrupting the supply, a large area is needed. Due to this limitation, in the early 20th century, slow sand filter became less attractive and the rapid filter became a greater interest (Haig *et al.*, 2011; Graham and Collins, 2014; Yamamura, 2014). In addition, the land in developing countries recently becomes a scarce resource due to the various land use interests (Görgen *et al.*, 2009). In order to overcome this limitation, the optimization on the design of slow sand filtration is required. However, the existence of some open questions in the current knowledge of slow sand filtration may restrict the optimization process. In 2014, Graham and Collins listed the open questions in the knowledge of slow sand filtration as follows:

a. a thorough, quantitative description of the principal process mechanisms;

b. correlation between the inlet water quality and the nature of the slow sand filtration dirty layer (*Schmutzdecke*);

c. elimination of natural and synthetic organic substances;

d. estimating the filter run time;

e. mechanisms of increasing filtration rates and filter run time; and

f. improvement on cleaning technologies.

This research focusses on the understanding the influence of operating variables on the filter performance, especially on the suspended solids removal, so that the optimization of the slow sand filtration design can be achieved. It is expected that the findings of this research can be adapted for the slow sand filter implementation especially in the developing countries. As an example, slow sand filter installed in Gunungkidul, in Java Island, Indonesia will be taken as a case study. Moreover, it is also expected that the results of this study may support further studies on the improvement of cleaning technologies.

2 Scientific Background

Review of previous literatures presented in this chapter is started from the topic of suspended solids. It is because the particular focus in this research was the suspended solids removal. Afterwards, description about slow sand filtration as one of the technologies to improve water quality and its elements is presented herein.

2.1 Suspended Solids

Suspended solids in water can be ranged from inert to highly biologically active particles, such as clay, silt, sewage solids, organic and biological sludge in water (EPA Ireland, 2001; Hudson, 2010). These solid materials which may be found within the water are aesthetically undesirable and to some extent may endanger human health (Hudson, 2010). The presence of suspended solids may alter the physical, chemical and biological properties of waterbody as a source of raw water for drinking purpose (Bilotta and Brazier, 2008). According to EPA Ireland (2001), suspended solids may contain of algal growth which can lead into eutrophic condition. Suspended solids may indicate the discharge from sandpits, quarries or mines and sewage. Deposition of suspended solids may be formed also on rivers of lakes bed. Moreover, EPA Ireland mentioned that suspended solids may intervene the aquatic plant life due to the reduction of light penetration in surface water body and affect fish life.

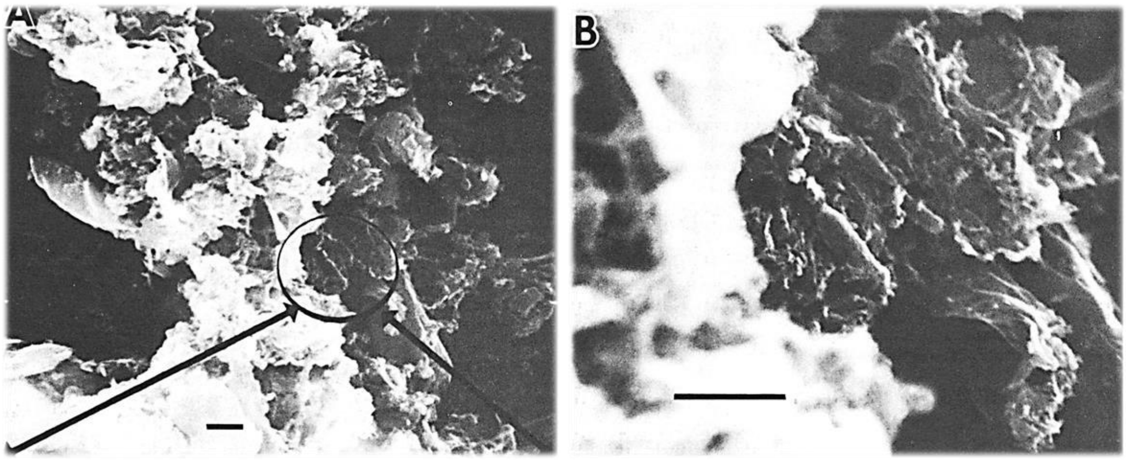


Figure 2. Scanning electron photomicrograph showing bacteria embedded in a particle. Bar: 1 µm. (LeChevallier *et al.*, 1981)

High levels of suspended solids also affect the disinfection process because the particles may protect the pathogen organisms (see Figure 2) and carry nutrients to encourage the bacteria growth (LeChevallier *et al.*, 1981; DeZuane, 1997; WHO, 2017). Hence, the suspended solids levels in water must be as low as possible before the disinfection process is introduced. Considering the effect both in water body and during the disinfection process, suspended solids is deemed to be one of the significant pollutants in water body. Concentration of suspended solids is expressed by a parameter so called Total Suspended Solids (TSS) which is a measure of dry particle mass (mg) in certain water volume (L) (Reynolds *et al.*, 2002; Bilotta and Brazier, 2008; Binnie and Kimber, 2013).

The degree of alteration in the water body properties due to the presence of suspended solids depends not only on some factors such as concentration, exposure period, chemical composition and particle size distribution but also the variation between organisms and environments (Bilotta and Brazier, 2008). Therefore, determination of water quality guidelines for TSS is complicated. According to the Guidelines for Drinking Water Quality, WHO does not establish the threshold value for TSS in raw water specifically (WHO, 2017). However, a threshold value is proposed by the European Communities Regulations for Quality of Surface Water Intended for the Abstraction of Drinking Water in 1989. According to the regulation, it is mandatory for raw water which is classified as category A1 to have a TSS value less than 50 mg/L (EPA Ireland, 2001). Raw water in category A1 has a high quality therefore requires only simple treatment (Erturk *et al.*, 2010).

Value of TSS can be determined by gravimetric method. This method consists of filtering certain volume of water through a filter paper, followed by drying the filter paper at 105 °C for two hours. The difference between the mass of dry filter paper before and after filtration is considered as mass of the suspended solids. The calculated TSS is the ratio between mass of the suspended solids and the volume of filtered water (EPA Ireland, 2001; Langenbach, 2010). Gravimetric analysis, however, has some disadvantages such as time demanding and its sensitivity (Al-Yaseri *et al.*, 2012). Hence, many researchers such as Grayson *et al.* (1996), Packman *et al.* (1999), Holliday *et al.* (2003) and Hannouche *et al.* (2011) correlated the TSS and turbidity because to measure the latter is easier and cheaper.

According to Binnie and Kimber (2013), turbidity is not directly related to the TSS concentration although the presence of suspended matter reduces the water clarity. It is because the correlation between TSS and turbidity depends on some factors such as the size, density, shape and type of the existing particles (Rügner *et al.*, 2013). Therefore depending on the particle types, turbidity can be a potential surrogate measurement to determine the TSS concentration (Packman *et al.*, 1999; Holliday *et al.*, 2003; Daphne *et al.*, 2011; Hannouche *et al.*, 2011; Al-Yaseri *et al.*, 2012; Rügner *et al.*, 2013).

Turbidity is defined as a measure of water clarity which is influenced by the existence of suspended materials (EPA Ireland, 2001; Al-Yaseri *et al.*, 2012). Turbidity has been deemed not only as a physical parameter due to its influence to the aesthetic appearance and psychological objections by the consumer, but also as a microbiological parameter (DeZuane, 1997). Turbidity may not be associated directly to the pathogenic organisms within the water but there is a strong connection between high turbidity level and high microorganisms content (Lee and Lin, 2007; Al-Yaseri *et al.*, 2012).

In order to determine the turbidity, formazine, a polymer formed from hydrazine and formaldehyde, is accepted as the primary standard for turbidity measurement because with this substance a repeatable accuracy of ± 1 % can be achieved (Hudson, 2010). Turbidity value is determined by a turbidimeter. This device beams a light through the sample and measures the amount of light absorbed and scattered by the solids at 90° (Safe Drinking Water Committee and National Research Council, 1977; Hudson, 2010; Binnie and Kimber, 2013). High turbidity values exhibit high concentration of suspended solids (Daphne *et al.*, 2011). However, amount of light scattered is not only influenced by the solid concentration but also by the scattering angle, solids size and shape, as well as refractive index of solids (Safe Drinking Water Committee and National Research Council, 1977; Hudson, 2010).

Although turbidity measurement cannot provide detailed information regarding the suspended solids such as their size number and mass or type of solids, the values indeed indicate whether or not other specific measurement shall be conducted such as for the determination of coliform or heavy metal. The turbidity values can also suggest the amount of chlorine required for the disinfection process (Safe Drinking Water Committee and National Research Council, 1977; LeChevallier *et al.*, 1981).

According to LeChevallier *et al.* (1981), the accepted turbidity level in drinking water has been standardized by the National Interim Primary Drinking Water Regulations that is promulgated on 24 December 1975 in accordance with the Safe Drinking Water Act. The recommended turbidity value is 1 NTU. It is allowed to have a turbidity value up to 5 NTU as far as it does not inhibit the disinfection process, avoid the maintenance of effective disinfectant, or hinder the microbiological determination (LeChevallier *et al.*, 1981). As one of the most important parameters, the turbidity values shall be monitored on a daily basis in every step of the drinking water treatment from the raw water to the distribution system (LeChevallier *et al.*, 1981; Tyagi *et al.*, 2009; Daphne *et al.*, 2011; WHO, 2017).

World Health Organization also proposed a standard value for the turbidity, which is similar to the National Interim Primary Drinking Water Regulations and the Safe Drinking Water Act. According to WHO (2017), turbidity should be reduced to less than 1 NTU to ensure an effective disinfection process. At the worst scenario when it is difficult to reach the proposed value, the turbidity level shall be maintained below 5 NTU. However, in order to compensate this high turbidity level, a higher chlorine doses or a longer contact time shall be given during the disinfection process to ensure the water quality. Hudson (2010) mentioned that turbidity value of 0.1 NTU at the outlet of treatment technology for drinking water will have low risk to human health. However the limits are that at the customer taps, turbidity values shall be set at 4 NTU while at the treatment plant it shall be 1 NTU.

2.2 Basic Design and Component of Slow Sand Filter

Basic design of slow sand filter is presented in Figure 3, consists of following parts (Huisman and Wood, 1974; Visscher, 1990; Campos, 2002):

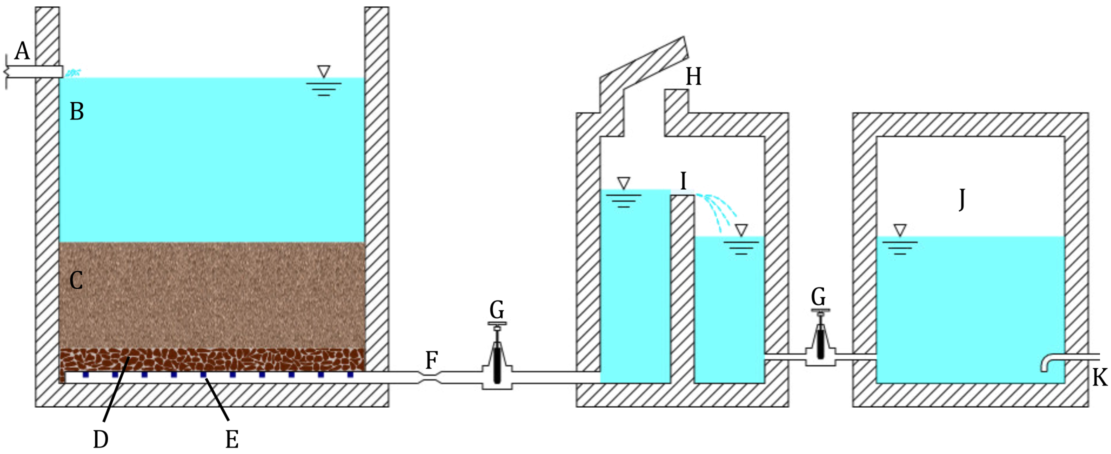
a. a supernatant layer which provides the pressure for the water to flow through the media and at the same time giving several hours retention for the raw water so that sedimentation, solids agglomeration and oxidation can occur;

b. a filter bed or sand bed where the purification mechanisms occur;

c. an under drainage system to support the filter media and minimize the obstacle for the treated water;

d. outlet chamber consists of two sections separated by a wall where on top of it is placed a weir to flow the treated water; and

e. a system of control valves which regulates the flow rate through the media.



A. Raw water inlet	E. Underdrainage	I. Weir
B. Supernatant layer	F. Venturimeter	J. Clean water reservoir
C. Filter or sand bed	G. Regulating valve	K. Clean water outlet
D. Supporting gravel	H. Ventilator	

Figure 3. Basic components of slow sand filtration (Huisman and Wood, 1974)

Related to the basic components of slow sand filtration, operating variables which can give significant effect to its performance are media grain size distribution, hydraulic loading rate, operation mode, filter bed depth, quality of influent and the sand type (Huisman and Wood, 1974; Bellamy *et al.*, 1985a; Muhammad *et al.*, 1996; Rolland *et al.*, 2009; Kandra *et al.*, 2014). Comparison of several recommended values for the design criteria can be found in Table 1 (Huisman and Wood, 1974; Visscher, 1990; Barrett *et al.*, 1991).

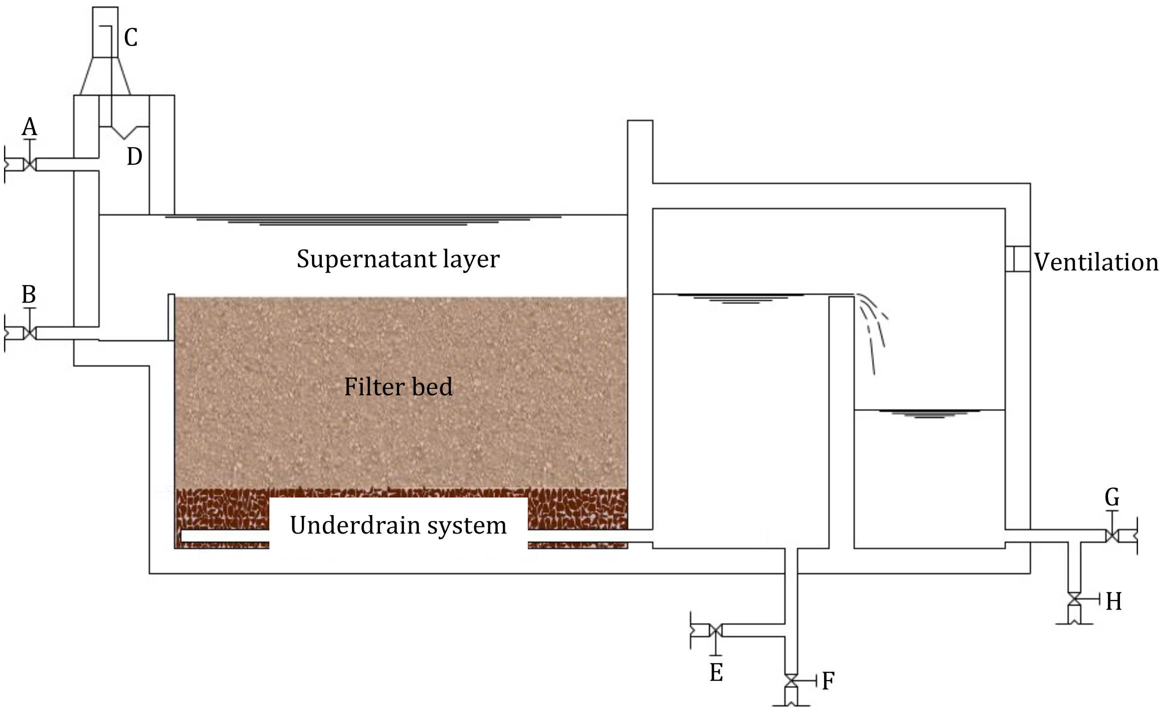
Table 1. Comparison of slow sand filtration design criteria according to different authors

Design Criteria	Recommended Values		
	Huisman and Wood (1974)	Visscher (1990)	Barrett et al. (1991)
Design period	7-10 years	10-15 years	20 years
Period of operation	24 hours/day	24 hours/day	24 hours/day
Hydraulic loading rate in the filters	0.1-0.4 m/h	0.1-0.2 m/h	0.04-0.4 m/h
Filter bed area	100-200 m^2/filter min. of 2 units	5-200 m^2/filter* min. of 2 units	$A = Q$/hydraulic loading rate** min. of 2 units
Thickness of sand bed:			
Initial	1.2-1.4 m	0.8-0.9 m	1.0-1.5 m
Minimum	0.7-0.9 m	0.5-0.6 m	0.3-0.8 m
Sand specification:			
Effective size d_{10}	0.15-0.35 mm	0.15-0.30 mm	0.2-0.3 mm
Uniformity coefficient (C_u)	<3 preferably < 2	<5 preferably <3	1.5-2 >3 for economic reasons is considerable
Height of underdrains (including gravel layer)	0.46 m	0.3-0.5 m	0.5-0.8 m
Height of supernatant layer	1.25 m	1.0 m	2.0-3.0 m

*To facilitate manual cleaning

**A stands for area; Q stands for debit

As one of the important operating variables, hydraulic loading rate must be maintained under proper rate to ensure the removal processes. According to Visscher (1990) and Sánchez *et al.* (2006), the proper hydraulic loading rate can be controlled either at the inlet (Figure 4) or at the outlet (Figure 5) of filter. Research to compare the influence of both systems to the filter performance has been conducted (Sánchez *et al.*, 2006). In terms of outlet quality, development of head loss and clogging period, both inlet and outlet controlled systems resulted in a similar filter performance.

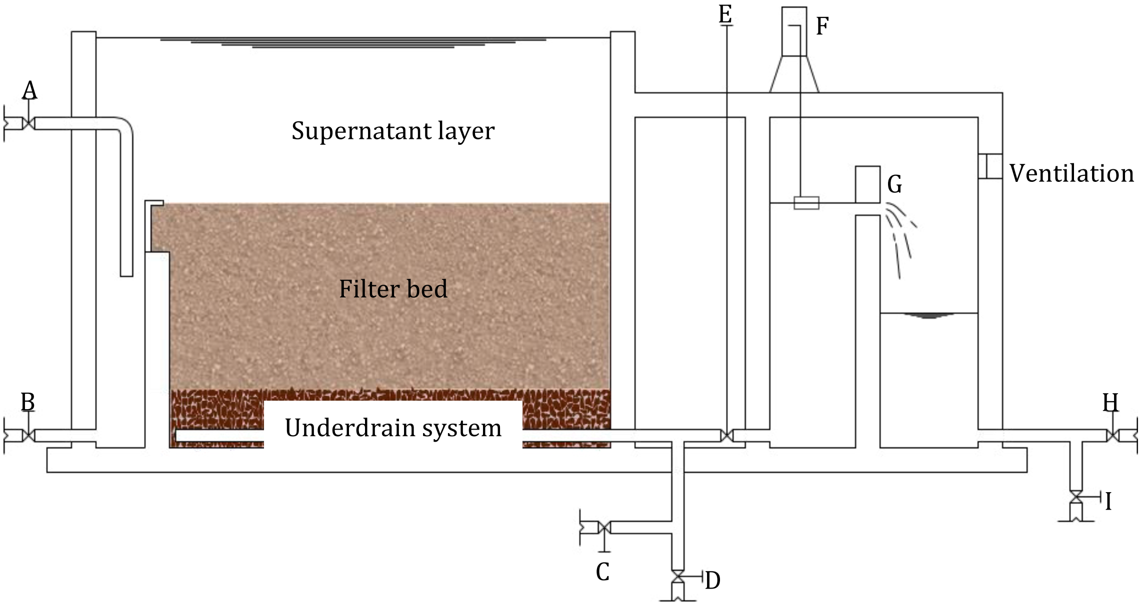


A. Raw water inlet valve for regulation of hydraulic loading rate
B. Valve for drainage of supernatant water
C. Inlet weir
D. Calibrated flow indicator
E. Valve for backfilling the filter bed with clean water
F. Valve for drainage of filter bed and outlet chamber
G. Valve for treated water distribution
H. Valve for delivery of treated water to waste

Figure 4. Slow sand filter scheme with inlet controlled system (Visscher, 1990)

In a slow sand filter with inlet controlled system, hydraulic loading rate is regulated by the raw water inlet valve (Visscher, 1990). This raw water inlet valve allows the water to flow in a constant rate to the filter unit leads into a constant hydraulic loading rate. Inside the system, a flow indicator is installed to measure the flow continuously (Visscher, 1990).

At the beginning of the operation, the supernatant layer is shallow therefore the retention time of raw water to be in this layer is shorter. Supernatant layer will gradually increase to compensate the head loss due to the development of *Schmutzdecke* at the filter bed surface (Sánchez *et al.*, 2006). When the supernatant level reaches the maximum, cleaning is needed. The advantage of the inlet control system is that it simplifies the filter operation. The rise of supernatant layer as a result of an increase of the head loss is directly visible (Visscher, 1990).



A. Raw water inlet valve
B. Valve to drain the supernatant water
C. Valve for backfilling the filter bed with clean water
D. Valve for drainage of filter bed and outlet chamber
E. Valve for regulation of the filtration rate
F. Calibrated flow indicator
G. Outlet weir
H. Valve for treated water distribution
I. Valve for delivery of treated water to waste

Figure 5. Slow sand filter scheme with outlet controlled system (Visscher, 1990)

Controlling the hydraulic loading rate at the outlet is the common method that is widely used (Sánchez *et al.*, 2006). Using this method, the supernatant layer is kept constant at the maximum level above the bed surface. The different level between the supernatant layer and the water overflow which is usually positioned equal to the bed surface, creates a pressure allowing the water percolates through the media. Along with the removal process, retained particles may increase the head loss, hence, influencing the hydraulic loading rate. In order to maintain the desired hydraulic loading rate, valve E should be gradually opened as a consequence of the head loss increase. This valve opening may cause a slight variation of the hydraulic loading rate. Moreover, the operator must adjust the outlet valve opening regularly so that the constant hydraulic loading rate can be maintained (Visscher, 1990).

In comparison to other water treatment technologies, some advantages of slow sand filtration are well-known and listed as follows (Huisman and Wood, 1974; Visscher, 1990; Cleary, 2005; Visscher, 2006; Gottinger *et al.*, 2011):

a. Slow sand filtration can effectively improve the water quality physically, chemically and microbiologically even when it is used as a single stage treatment. Table 2 shows the examples of removal efficiencies of slow sand filtration based on the results of some previous studies by Slezak and Sims (1984), Bellamy *et al.* (1985a), Bellamy *et al.* (1985b), Visscher (1990), Collins *et al.* (1991), Galvis (1999), Logsdon *et al.* (2002) and Kaya and Takeuchi (2014). However, from these results it can be inferred that the slow sand filtration cannot directly produce drinkable water without further step of treatment because this technology alone cannot achieve 100 % of bacteria and viruses removal.

b. Slow sand filter is an uncomplicated technology in respect to the construction, operation and maintenance therefore the cost can be maintained low.

c. During the operation of slow sand filter, chemicals are not required.

d. Low energy is required because the filter operates exploiting only the gravity flow.

e. Slow sand filtration systems produce less dangerous waste compared to other methods because the sludge resulted during filter scraping is handled in a dry state and this material can be used as fertilizer.

f. Cleaning process requires only a little amount of water, thus conservation of water can be managed.

In spite of its advantages, the disadvantages of slow sand filter is also reported, as presented below (Huisman and Wood, 1974; Visscher, 1990; Logsdon *et al.*, 2002; Gottinger *et al.*, 2011):

a. Due to its low velocity, a large area is needed to encounter the demand.

b. Slow sand filter may not be suitable for cold climates because the filter operation at very low temperature influences the filter performance adversely. Therefore, an additional expensive system against freezing should be installed.

c. Slow sand filtration is vulnerable to high turbidity as it accelerates the clogging period.

d. In some countries where the construction methods are mechanized, for instance in the Netherlands, initial cost of slow sand filter may be higher than rapid filter.

e. The growth of certain types of algae may require a more frequent cleaning due to the premature clogging.

Table 2. Removal efficiencies of slow sand filtration

Parameter	Effluent or removal efficiency	Reference(s)
Turbidity	< 1 NTU*	Slezak and Sims (1984); Visscher (1990); Collins *et al.* (1991); Galvis (1999)
Color	30-100 % 25-40 %	Visscher (1990) Galvis (1999)
Total coliforms	96-99.9 % 98.9 %	Bellamy *et al.* (1985a) Bellamy *et al.* (1985b)
Fecal coliforms	95-97 % 98 % 1-3 log units	Bellamy *et al.* (1985a) Bellamy *et al.* (1985b) Collins *et al.* (1991)
Enteric viruses	2-4 log units 99-99.99 %	Collins *et al.* (1991) Galvis (1999)
Giardia cysts	>99.9 % 2-4 log units 99-99.99 %	Bellamy *et al.* (1985a); Bellamy *et al.* (1985b) Collins *et al.* (1991) Galvis (1999)
Cryptosporidium oocysts	>99 %	Galvis (1999)
Standard plate count bacteria	>99 % 87-91 %	Bellamy *et al.* (1985a) Bellamy *et al.* (1985b)
Organic matter	60-75 %	Visscher (1990)
Biodegradable dissolved organic carbon	<50 %	Collins *et al.* (1991)
Iron and manganese	Largely removed 30-90 % >99.9 %	Visscher (1990) Galvis (1999) Kaya and Takeuchi (2014)
Heavy metals	30-95 %	Visscher (1990)
Trihalomethane precursors	<25 %	Collins *et al.* (1991)

*Nephelometric Turbidity Unit

2.3 Hydraulics of Filtration

In the theory of granular filtration, discussion about hydraulics is started by determining the flow types. Fluid flow may be classified as laminar, turbulent and transitional (Webber, 1965; Bardet, 1997). Webber stated that laminar flow occurs when the velocity is low and constant in such a way that the particles move parallel to the flow path. Adversely, the particle velocity during turbulent flow is high and fluctuated causing the particles motion is not in line with the flow path. Bardet define transitional as a type of flow between the lamina and turbulent flows. The simplest method to characterize the fluid type is by using the Reynolds number (*Re*). Following is the formula to calculate the *Re* (Binnie and Kimber, 2013):

$$Re = \frac{\rho \cdot v \cdot D}{\eta} \tag{1}$$

where ρ is the density of water, v is hydraulic loading rate, D is the particle diameter and η is the dynamic viscosity of fluid which in this research is water. According to Welty (2008), when the *Re* is below 2300, the flow is classified as laminar. A flow is transitional when 2300 < *Re* < 3000 and turbulent flow occurs if the *Re* is above 3000.

Low hydraulic loading rate in slow sand filtration leads into very small *Re* thus the flow regime is categorized as laminar flow (Campos *et al.*, 2006). Jabur *et al.* (2005) described that in slow sand filtration, *Re* < 2. Therefore, Darcy's Law which stating that hydraulic loading rate is proportional to the difference of pressure can be applied in this system (Ives, 1987). An assumption in the application of Darcy's law is that the flow is steady, laminar, no change in viscosity (inviscid) and volume (incompressible) (Budhu, 2015). This equation from Darcy's law can describe the flow in porous media. According to the experiments done by Darcy, flow velocity v is influenced by the hydraulic conductivity k and hydraulic gradient i (Bardet, 1997):

$$v = k \cdot i \tag{2}$$

Filtration velocity v or hydraulic loading rate can be determined by dividing the volumetric flowrate Q by the specimen cross-sectional area A (see Equation 3) (Sherard *et al.*, 1984). The value of Q can be obtained by dividing the volume and time t of water collected. The A depends on the diameter of column D.

$$v = Hydraulic\ Loading\ Rate = \frac{Q}{A} = \frac{Volume/_t}{\pi \cdot D^2/_4} \tag{3}$$

Hydraulic gradient i is the ratio of different head drop Δh and the bed depth L (Bardet, 1997):

$$i = \frac{\Delta h}{L} \tag{4}$$

Hydraulic conductivity is one of parameters generally used to characterize transport phenomena in porous media (Koponen *et al.*, 1997). Hydraulic conductivity describes how ease the water flow through the media. There are many factors influencing hydraulic conductivity in sand filtration such as size and shape of grains, homogeneity, size and arrangement of voids which are represented by void ratio and porosity, layering and fissuring, degree of saturation, fluid properties i.e. viscosity and temperature, fissuring, compression or stress level and particles loading (Bardet, 1997; Deb and Shukla, 2012; Budhu, 2015; Le Coustumer *et al.*, 2012).

Coarse grains tend to have a higher hydraulic conductivity compared to the finer grains. Fine fraction presence in the soil may significantly reduce the hydraulic conductivity (Budhu, 2015). As a provisional basis for this fine fraction, effective size d_{10} (mm) is used. The term d_{10} represents the grain size which is 10 % finer by weight. The d_{10} is used as one of the parameters because Hazen (1905) found out that fine fraction represented by d_{10} mainly determines the characteristic of the sand. Budhu (2015) also mentioned that this portion will result relatively the same effect as irregular particles. According to the d_{10} value, the sand is classified as fine or coarse. Low d_{10} value represents finer grains and vice versa. Empirical relationship between the d_{10} and hydraulic conductivity k_H (cm/s) is shown by Hazen's formula as follows (Bardet, 1997; Budhu, 2015):

$$k_H = C_H \cdot d_{10}^2 \tag{5}$$

where C_H is the Hazen constant which ranges between 0.4 and 1.4. This constant reflects the different type of soil. For fine and uniform sand, C_H is typically 1.0. Another method to determine the C_H by considering the porosity n is presented by Naeej *et al.* (2017) as follows:

$$C_H = \frac{g}{\nu} \times 6 \times 10^{-4} \times [1 + 10(n - 0.26)] \tag{6}$$

In this study, the gravitational acceleration g is assumed to be 9.81 m/s^2 and the kinematic viscosity ν is 1×10^{-6} m^2/s. Hazen's formula is usually used to estimate the hydraulic conductivity value for coarse soils (Budhu, 2015). Calculation of empirical hydraulic conductivity based on Hazen's formula was done using Equation 5 if the following requirements are fulfilled: 0.1 mm $\leq d_{10} \leq$ 3 mm and $C_u < 5$.

Estimation of hydraulic conductivity of filter media which did not meet the requirements for Hazen's formula was determined using the Beyer's formula. The formula from Beyer as shown is Equation 7 is more suitable for finer grain size distribution (0.06 mm $\leq d_{10} \leq$ 0.6 mm and $C_u < 20$) (Vienken and Dietrich, 2011; Naeej *et al.*, 2017):

$$k_B = C_B \cdot d_{10}^2 \tag{7}$$

The constant after Beyer C_B is also influenced by the gravitational acceleration g, kinematic viscosity ν and the homogeneity of the sand which is represented by uniformity coefficient C_u. Uniformity coefficient C_u, which characterizes the homogeneity of the sand, is the ratio of d_{60} to d_{10} (Bardet, 1997). The d_{60} represents the grain size which is 60 % finer by weight. The constant C_B can be calculated using following formula (Naeej *et al.*, 2017):

$$C_B = \frac{g}{v} \times 6 \times 10^{-4} \times log \frac{500}{C_u} \tag{8}$$

Large voids are not directly related to high porosity which will result into higher hydraulic conductivity. Figure 6 illustrates a sample of soil with total volume V and weight W. This soil sample consists of solid, water and air. When each constituent is grouped, the solid has a weight W_s and volume V_s. The weight and the volume of water are represented by W_w and V_w respectively. The air is weightless with a volume of V_a. Total volume of voids V_v is composed by V_w and V_a.

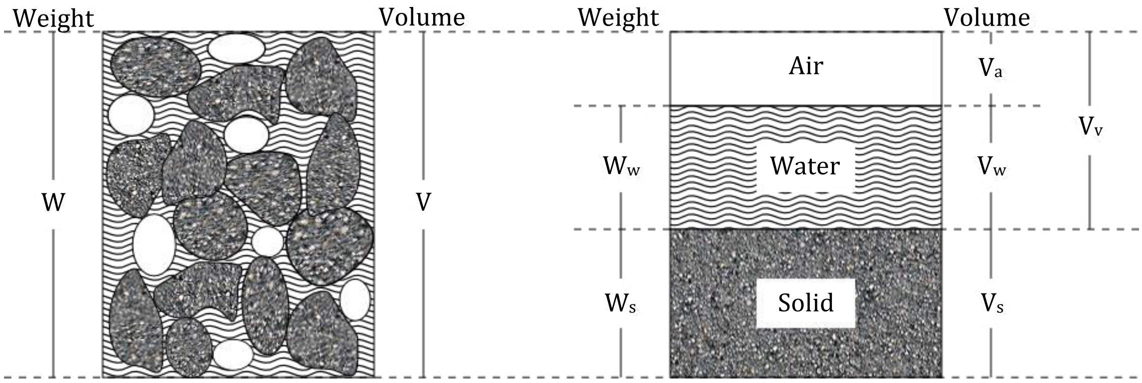


Figure 6. Weight and volume of a soil sample (left) and weight and volume of solid, water and air constitutent (right) (Bardet, 1997)

Void ratio e is the ratio of total voids volume to the solid volume (see Equation 9). In a sand bed with heterogeneous grain size, void ratio is reduced thus hydraulic conductivity is lower (Mbonimpa *et al.*, 2002).

$$e = \frac{V_v}{V_s} \tag{9}$$

Porosity describes the total pores exist within the filter bed. Porosity n is the ratio of total voids volume to the total volume as shown in Equation10 (Bardet, 1997):

$$n = \frac{V_v}{V} \tag{10}$$

When the value of V_v and V_s are difficult to be measured, the void ratio e can be determined based on the specific gravity G_s of the sand, water unit weight γ_w and dry unit weight γ_d. Equation 11 shows the relation among e, G_s, γ_w and γ_d (Bardet, 1997). Specific gravity G_s is a unit less expression which describes the ratio between unit masses of soil and water (Bardet, 1997). Determination of G_s can be done by laboratory test and the method is described in Section 4.2.1. In this study, the γ_w is assumed to be 9.81 kN/m^3. The γ_d is obtained by dividing the dry sample weight by the volume of sample. The dry sample weight in Newton is a product of dry sample mass in grams multiplied by the gravitational acceleration.

$$e = \frac{G_s \cdot \gamma_w}{\gamma_d} - 1 \tag{11}$$

Porosity *n* can be determined from the value of *e* with following equation (Bardet, 1997):

$$n = \frac{e}{1 + e} \tag{12}$$

According to Koponen *et al.* (1997), the interconnected pores are crucial because those contribute to the flow in porous media. How the voids connect one another determines greatly the hydraulic conductivity.

By considering the correlation of hydraulic conductivity and porosity, velocity through the void spaces or seepage velocity v_s can be calculated using a formula as follows (Budhu, 2015):

$$v_s = \frac{k}{n} \cdot i \tag{13}$$

Based on the value of porosity, an empirical hydraulic conductivity is determined using the Kozeny-Carman's formula as follows (Naeej *et al.*, 2017):

$$k_{KC} = \frac{g}{v} \times 8.3 \times 10^{-3} \times \left(\frac{n^3}{1 - n^2}\right) \times d_{10}^2 \tag{14}$$

Hydraulic conductivity is high in loose state soil layers leading to a very high seepage velocity. In loose state soil layers, the existence of fissures may also increase the hydraulic conductivity degree (Budhu, 2015).

Degree of saturation influences significantly the water flow in porous media. If the voids of soil sample are filled completely with water, fully saturated condition is achieved. Degree of saturation S_r (%) is calculated by comparing the water volume V_w and total voids volume V_v (Bardet, 1997):

$$S_r = \frac{V_w}{V_v} \times 100 \tag{15}$$

The possibility of fully saturated condition is very low due to the presence of entrapped air within the soil sample. Consequently, the entrapped air reduce the hydraulic conductivity due to the capillary action or soil suction (Budhu, 2015).

Viscosity is a temperature dependent parameter. When the temperature increases, the viscosity of fluid decreases (Cho *et al.*, 1999). In a low viscosity, it is easier for the fluid to pass through the sand bed thus the hydraulic conductivity is higher (Budhu, 2015).

Compression of the soil bed reduces the hydraulic conductivity due to the higher stress level. There are two processes of compression i.e. compaction and consolidation. Compaction decreases the total volume of voids, thus, it reduces the sand bed capability to convey the water (Bardet, 1997; Hatt *et al.*, 2008). Consolidation occurs through a gradual flow of water independently of the clogging effects on the surface of filter bed (Hatt *et al.*, 2008).

In the filtration process, impurities or suspended solids are removed from the raw water. These impurities are mostly deposited at the surface of filter bed. Due to the very fine size of the retained solid, the hydraulic conductivity is significantly decreased (Le Coustumer *et al.*, 2012).

The hydraulic conductivity can be measured in–situ using a permeameter. In the laboratory scale, hydraulic conductivity can be determined either by constant head or falling head test (Figure 7).

Constant head test is usually used to determine the hydraulic conductivity of coarse-grained soils such as clean sand and gravels ($k \geq 10^{-3}$) (Bardet, 1997). In this type of test, water is flowing through a bed of soil under a constant head as shown in Figure 7a. Hydraulic conductivity in vertical direction k can be determined by (Budhu, 2015):

$$k = \frac{Q \cdot L}{A \cdot \Delta h} \tag{16}$$

where Q is the volumetric flowrate (see Equation 3), L is the thickness of soil bed, A is the cross-sectional area and Δh is the head difference of inlet and outlet.

The water flow in the less permeable soils such as fine sand ($k \leq 10^{-3}$ cm/s) is too slow, that the constant head test requires unreasonable measurement time. Therefore, for this type of soil, hydraulic conductivity is determined by falling head test. In the falling head test, water flows through a bed of soil with decreasing level as illustrated in Figure 7b. Hydraulic conductivity k is calculated using the following formula (Bardet, 1997; Budhu, 2015):

$$k = \frac{a \cdot L}{A \cdot (t_2 - t_1)} ln\left(\frac{h_1}{h_2}\right) \tag{17}$$

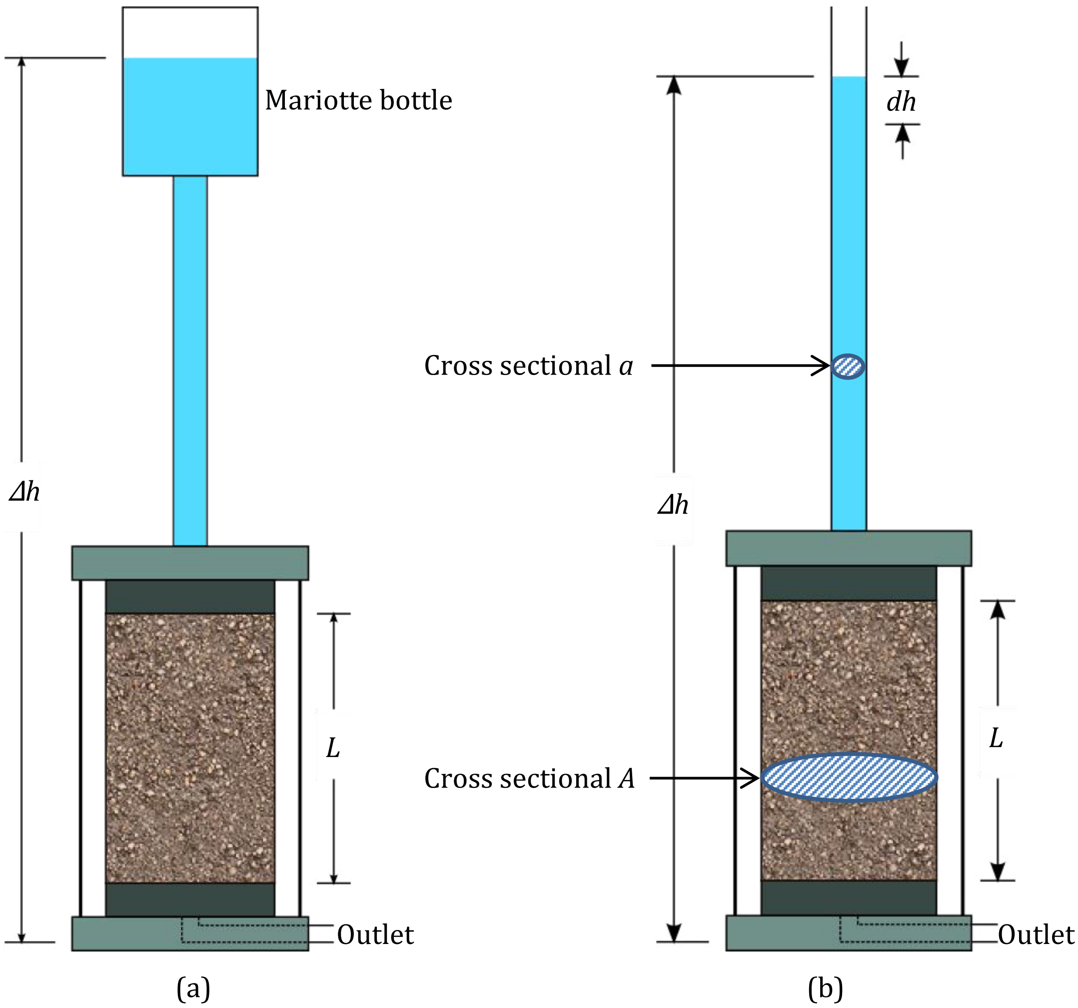


Figure 7. A scheme of (a) constant head test and (b) falling head test (Budhu, 2015)

2.4 Head Loss and Clogging Phenomena

Head loss, in this study, is a phenomenon in slow sand filtration where the downward raw water flow is resisted by the existence of sand bed (Huisman and Wood, 1974). Accumulation of impurities on the surface of filter bed is also responsible for the progressive increase of head loss during filter operation (Graham and Collins, 2014). This phenomenon can be describe as the difference between the head of the water above and below the sand bed and it represents the frictional resistance of the sand layer (Hazen, 1905).

According to Holdich (2002), head loss is the inverse of hydraulic conductivity. High head loss is related to the high fluid viscosity μ and low hydraulic conductivity as formulated in the following:

$$i = \frac{\mu}{k} \cdot Hydraulic\ Loading\ Rate \tag{18}$$

Huisman and Wood (1974) proposed a simple method to calculate the head loss H which is associated with hydraulic loading rate (Naghavi and Malone, 1986) within a sand bed thickness of h as follows:

$$H = \frac{Hydraulic\ Loading\ Rate}{k} \cdot h \tag{19}$$

At the beginning of the filter operation, the head loss is dominantly dependent on the grain size distribution of media, bed depth and hydraulic loading rate (Naghavi and Malone, 1986; Zhu *et al.*, 1996; Mandloi *et al.*, 2004). Figure 8 shows how high initial head loss can be associated with lower median grain size diameter and greater thickness of bed depth.

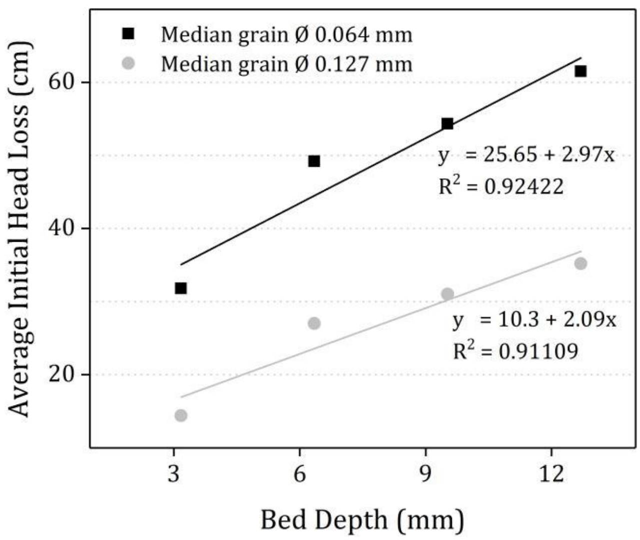


Figure 8. Correlation of average initial head loss and bed depth after Naghavi and Malone (1986)

Head loss gradually increases due to the deposition of sediment from the raw water and mostly occurs at the top layer of sand bed (Hazen, 1905; Farooq and Al-Yousef, 1993; Holdich, 2002; Aronino *et al.*, 2009).

Hydraulic gradient or gradient of total head (Bardet, 1997) can be used as an indicator of development head loss (Darby *et al.*, 1992). Head loss development in filter bed is determined by media grain size, bed depth, hydraulic conductivity, media shape, bed porosity, hydraulic loading rate, water viscosity and density, concentration and size of suspended solids in water, volume of treated water and the ratio of filter diameter to media effective size(Yao *et al.*, 1971; Lang *et al.*, 1993; Boller and Kavanaugh, 1995; Trussell and Chang, 1999; Holdich, 2002; Puig-Bargués *et al.*, 2005; Mesquita *et al.*, 2012). Due to the limited literatures in slow sand filtration about head loss development, references cited herein are predominantly from the research in deep bed filtration.

Head loss is always dependent on the hydraulic conductivity of filter bed. Hydraulic conductivity has an inverse relationship with the head loss. Under a constant flow, lower hydraulic conductivity leads into the increase of head loss (Mays and Hunt, 2005). One of factors which affect the hydraulic conductivity and head loss is media shape (Bardet, 1997). According to Bardet, especially related to the coefficient values of grain shape and the empirical hydraulic conductivity, the more irregular the media shape, the lower the hydraulic conductivity is. This means that the more rounded media shape will result in a lower head loss. However, Sperry and Peirce (1995) concluded that media size is more significant for predicting the hydraulic conductivity rather than media shape. This conclusion is confirmed by Trussell and Chang (1999) which stated that media shape has much less influence on the head loss compared to the impact of porosity and media size.

Bed porosity is inversely proportional to the head loss as the higher bed porosity, the lower the head loss is (Trussell and Chang, 1999). Deposition of suspended solids in filter bed reduces the overall porosity (Tobiason and Vigneswaran, 1994). The decrease in porosity increases the tortuosity of flow in filter bed and consequently, head loss (Boller and Kavanaugh, 1995). Related to media size, O'Melia and Ali (1978) stated that its impact on the head loss development is less significant compared to the effect of suspended solids concentration and size. Based on the study of O'Melia and Ali, raw water with low concentration of suspended solids results in slow increase of head loss. This result was verified by Vigneswaran and Song (1986). Adin and Elimelech (1989) disproved the result of O'Melia and Ali, particularly on the impact of media size. According to their study, Adin and Elimelech found that rate of head loss increase is strongly dependent on the media size. Finer media produce much higher head loss increase due to the surface removal of suspended solids, rather than the coarser media. Another study by Boller and Kavanaugh (1995) also contradicts to O'Melia and Ali in regard to media size. However, Boller and Kavanaugh showed contrary results to Adin and Elimelech. In their study, head loss increase in coarser media size is larger than in finer media size. Size of suspended solids affects the head loss development in an inverse way. Suspended solids with larger size do not produce enormous head loss, meanwhile the submicron solids do (O'Melia and Ali, 1978). This result was confirmed by Tobiason and Vigneswaran (1994) and Boller and Kavanaugh where smaller solids result in higher head loss per unit mass deposited.

Hydraulic loading rate has an essential impact on the head loss development. Adin and Elimelech (1989) observed that rapid head loss increase occurs in a filter bed operated higher hydraulic loading rate. On the contrary, Veerapaneni and Wiesner (1997) found out that lower hydraulic loading rate generates steep increases in head loss. It is because deposits of suspended solid occupy more pore spaces in filter bed under low hydraulic loading rate. Therefore, the drag loss for the water to flow is higher and consequently the head loss is higher. Disproving the both studies of Adin and Elimelech (1989) and Veerapaneni and Wiesner (1997), effect of hydraulic loading rate was found to be insignificant on the head loss development by Boller and Kavanaugh (1995).

Progressive increase of head loss can be associated and used to predict the clogging rate (Puig-Bargués *et al.*, 2005). Based on its definition, clogging is a condition when the hydraulic conductivity decreases and water cannot percolate easily through the sand bed due to sediment accumulation and deposition in the filter from the total period of operation (Rodgers *et al.*, 2004; Kandra *et al.*, 2014; Mercado, Jean Margaret R *et al.*, 2015). Clogging is a result of physical, biological and chemical processes (Pérez Paricio, 2001). The terms physical process refers to the attachments or detachment of suspended solids into the sand grains (McDowell-Boyer *et al.*, 1986). Biological process involves the accumulation and growth of microorganisms in porous media (Vandevivere *et al.*, 1995). Chemical clogging seldom occurs unless there is a chemical interaction between the dissolved salt in the water and the porous media (Rice, 1974).

Clogging that occurs in sand filtration is regarded as a surface phenomenon (Rodgers *et al.*, 2004; Leverenz *et al.*, 2009; Le Coustumer *et al.*, 2012). This surface phenomenon involves the decline of pore space caused by suspended solids and bacterial growths on the captured or dissolved solids, and reopening of pore space caused by bacterial decomposition and the reduction of bacterial growths during the resting period (Leverenz *et al.*, 2009).

In slow sand filtration, at the beginning of the filter run, the sand characteristics such as its size influenced the clogging layer development (Elisson, 2002). Fine sand tends to clog faster than the coarser. However, once the clogging layer is formed, development of the clogging layer does not depend on the sand bed characteristics anymore (Kropf *et al.*, 1977). Clogging is a serious problem which influence the filter performance (Kandra *et al.*, 2010). In the worst case, clogging may provoke a breakthrough in the filter bed (Hazen, 1905; Vries, 1972; Kandra *et al.*, 2010).

In practical use, high initial head loss may not be beneficial. It is because the time to reach the terminal head loss or clogging period is shorter. In order to ensure a consistently well performance, a filter shall be designed and operated in a manner where the time to reach the terminal head loss is considerably shorter than the time to reach the breakthrough. According to Hazen (1905), breakthrough occurs when the pressure for the water to flow becomes very high that the filter cake will no longer able to resist it. The filter cake will be broken allowing the water to flow with a huge increase of the loading rates. As a consequence, the breakthrough causes the decreased removal efficiency (Hazen, 1905). From this point of view, head loss is not only a very significant parameter but also a dominant design constraint (Boller and Kavanaugh, 1995).

Maintenance of filter when terminal head loss or clogging is reached normally involves scraping of top layers to remove the clogging layer. Other method that can be done to put the slow sand filter back into service is by filter cake harrowing (Collins *et al.*, 1991; Österdahl, 2015). Filter harrowing is done by draining the supernatant water into only around 30 cm above the sand surface. Then the top 30 cm sand medium is raked –either manually or using a machine– so that the colloidal debris is loosened and caught by the moving water stream. The dirty water is not discharged through the filter bed but at the surface. This harrowing is believed to be a better method because it requires less time and labor compared to the normal scraping. Moreover, the filter can be put back into service faster without compromising the removal efficiency (Collins *et al.*, 1991).

2.5 Removal Mechanisms

Fundamental purpose of filtration is to remove the impurities from the water by passing it through sand bed. Removal mechanisms and inactivation of microorganisms are mostly related to a thin layer so called *Schmutzdecke* or 'dirty layer' at the surface of filter bed (Weber-Shirk and Dick, 1997). *Schmutzdecke*, together with low hydraulic loading rate and fine sand size, encourages the filter to achieve high efficiency of treatment (Campos *et al.*, 2002).

For more than a century, the role of *Schmutzdecke* in the removal mechanisms had been argued due to its various definitions. Hazen (1905) expressed the *Schmutzdecke* as a sediment layer resulted from coarser particles in the water that are restrained on the surface of sand bed. This layer will then become another filter that is much finer than the sand. Huisman and Wood (1974), Ellis (1987) and Binnie and Kimber (2013) had similar definition on *Schmutzdecke* stating that it is a thin slimy mat or a biologically active mat formed on the surface of sand bed composed of humus, sand, algae, plankton, diatoms, protozoa, metazoan, rotifiers and bacteria. Cleasby *et al.* (1984) and Bellamy *et al.* (1985b) stated that *Schmutzdecke* consists of inert deposits and living organisms that develops on the surface of sand bed. Weber-Shirk and Dick summarized those various definitions of *Schmutzdecke* as follows:

a. particle deposition which forms a layer on the surface of filter bed,

b. a surface skin formed by biological growth, and

c. a biologically active zone within the filter bed.

At the beginning of the filter operation,the *Schmutzdecke* is formed due to the physical process (Campos, 2002; Ellis *et al.*, 2009). This physical removal is regarded as the principal removal mechanisms in slow sand filtration (Campos, 2002). Thus, in order to understand the removal mechanisms in slow sand filtration, the focus in this study was on the suspended solids removal. Considering this focus of research, the most suitable definition of *Schmutzdecke* is the layer of solids deposition on the surface of filter bed. Another term that is more suitable to specify this solids deposition is 'filter cake' (Weber-Shirk and Dick, 1997). From this point on, the term of filter cake will be used herein.

Generally, removal mechanisms of suspended solids by filtration consist of two sequential steps: transport and attachment processes (Elimelech and O'Melia, 1990a). These mechanisms that is responsible for suspended solids removal in slow sand filtration are influenced by many variables such as the retention site, retention forces, particle size, type of flow and transport or capture mechanisms (Herzig *et al.*, 1970; Yao *et al.*, 1971; Huisman and Wood, 1974; McDowell-Boyer *et al.*, 1986).

2.5.1 Transport Mechanisms

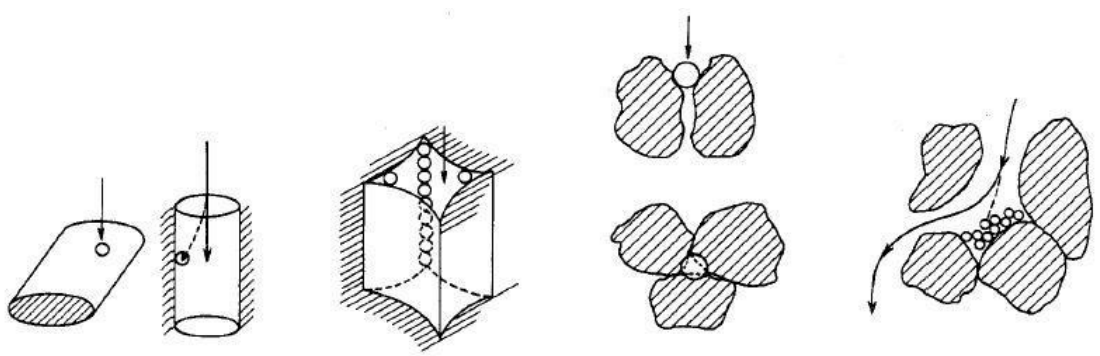
Particles are brought into contact to the potential retention site where it can be remained or transported by the stream during the flow through the sand bed (Herzig *et al.*, 1970). There are four possible locations where the suspended solids may be collected as illustrated in Figure 9:

a. surface, where suspended solid may have contact with and retained on;

b. crevice, where suspended solids are wedged in between two convex surfaces of two grains;

c. constriction, where suspended solid is retained among grains because its size is bigger than the pore size; and

d. cavern, where the suspended solids are remained in such a sheltered pocket formed by several sand grains.



(a) (b) (c) (d)

Figure 9. Retention sites of suspended solids: (a). surface; (b). crevice; (c). constriction; and (d). cavern (Herzig *et al.*, 1970)

Transport mechanisms are categorized into six types: sedimentation, interception, inertia, diffusion or Brownian motion, hydrodynamic effects and mass attraction or van der Waals force (Herzig *et al.*, 1970; Yao *et al.*, 1971; Huisman and Wood, 1974). By considering a single grain of filter media as a collector, Yao *et al.* illustrated the transport mechanisms as seen in Figure 10. Darby and Lawler (1990) mentioned that particle size distribution determines the dominant transport mechanism whether it is sedimentation or interception or Brownian motion. The first two types of transport mechanisms occur when the suspended solids are >1 μm (Yao *et al.*, 1971; O'Melia and Ali, 1978). Meanwhile, Brownian motion will play more important role for the particles having the size of < 1 μm (Keller and Auset, 2007). In this study, in order to study more about the head loss development and ripening period in the slow sand filtration, particle size distribution also needs to be considered since it is impossible to rely only on the measurement of turbidity or TSS (Darby and Lawler, 1990).

Sedimentation occurs when the density of solids is higher than the water density. In this case, the velocity of the particle is no longer the same as the water due to the gravitational force (Herzig *et al.*, 1970; Yao *et al.*, 1971; Ives, 1987). Hence, the particles are precipitated onto the collector. Temperature is also influencing sedimentation efficiency since it affects the viscosity of water. The higher the temperature is, the lower the viscosity allowing a faster settlement of particle (Ives, 1987).

Another factor affecting sedimentation efficiency is the ratio between the surface loading rate and the settling velocity of suspended particles. If the settling velocity is equal to or greater than the surface loading, removal by sedimentation can occur (Huisman and Wood, 1974). Settling velocity will be discussed particularly in the Section 2.6.

Interception is due to the flow of suspended particles which follow the trajectory and at some points come into contact with the collector (Yao *et al.*, 1971). According to Keller and Auset (2007), interception is not only a function of hydraulic loading rate but also of diameter ratio between suspended solids and the sand grain as well as porosity. Probability of interception will decrease if the hydraulic loading rate is high.

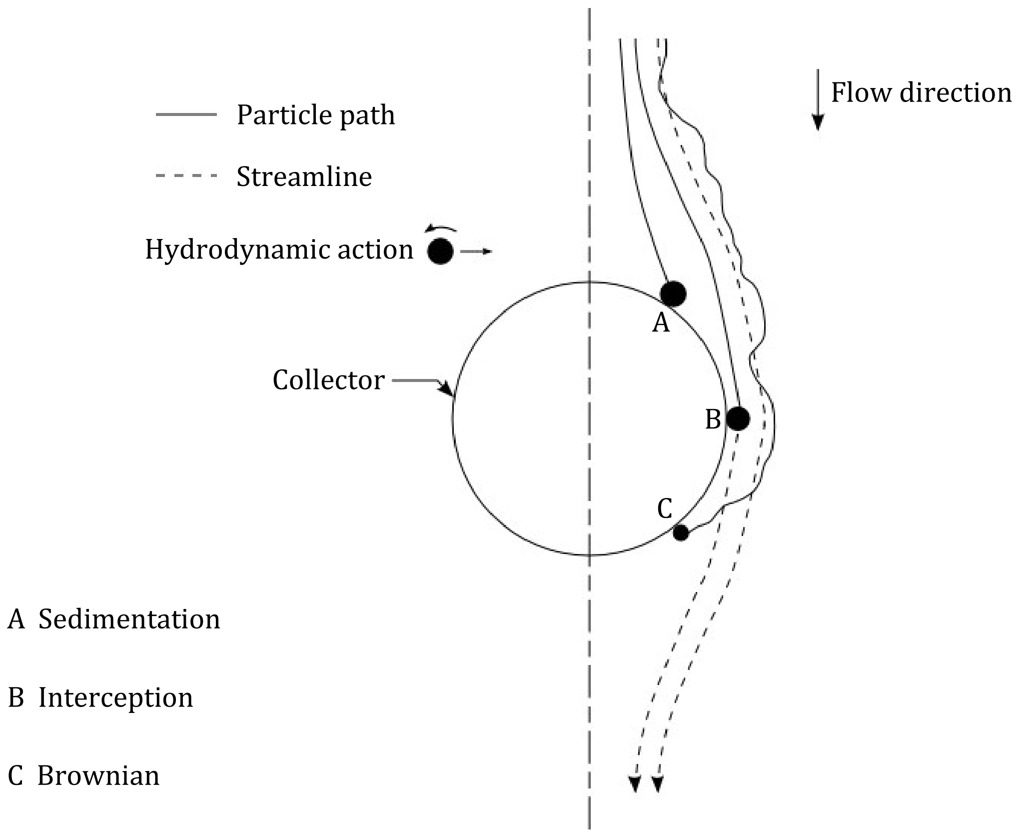


Figure 10. Basic transport mechanisms in sand filtration (Yao *et al.*, 1971; Bradford *et al.*, 2002; Binnie and Kimber, 2013)

Inertia is the tendency of a particle to remain in its own trajectory (Zamani and Maini, 2009). Due to their inertia, it is difficult for the particles to follow the same trajectory as the water (Herzig *et al.*, 1970). Deviation of the streamlines cannot be avoided and at some points the particles are brought into contact with the grains. However, if the hydraulic loading rate and Reynolds number are low, inertia is not significant (Binnie and Kimber, 2013).

Difussion or Brownian motion is induced by the collision between liquid molecules and the suspended solid causing a random movement (Yao *et al.*, 1971). Diffusion enables particles to come into contact and detained to the area that is not flooded by the suspension (Herzig *et al.*, 1970).

Hydrodynamic effects occur due to the nonuniform velocities and the nonsphericity of particles (Herzig *et al.*, 1970; Ives, 1987). Largest velocity is at the center of particles and declines approaching the grain surface. The velocity gradient from one side to the other causes particles to rotate (Binnie and Kimber, 2013). Nonsphericity of particles leads into imbalance forces which cause the particles to turn and twist during their move through the water. Combination of rotations, turns and twists causes lateral forces which divert the particles from their streamlines allowing them to travel in a random path, hence, it increases the contact probability between the particles and the sand grains (Ives, 1987).

Mass attraction or van der Waals force does not only influence the transport mechanisms but also attachment mechanisms (Huisman and Wood, 1974). Van der Waals force is influenced by the size of the interacting particles, the distance between particles and collector, and Hamaker constant of interacting media (Herzig *et al.*, 1970; Elimelech and O'Melia, 1990b). Hamaker constant reflects the interaction between the interacting materials and the intervening media (Bergström, 1997). Van der Waals force is significant when the distance between two particles is close (Huisman and Wood, 1974).

McDowell-Boyer *et al.* (1986) summarized three mechanisms that impede the suspended solids migration during the transport processes through porous media as illustrated in Figure 11. These mechanisms depend on the size of suspended solids.

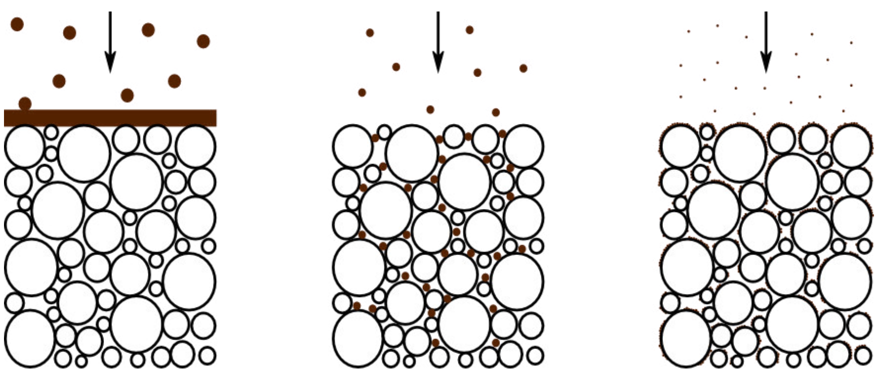


Figure 11. Filtration mechanisms: filter cake formation (left); straining (middle); and physical-chemical filtration (right) (McDowell-Boyer *et al.*, 1986)

When the particles are larger than the pore size, their penetration into the sand bed is limited. They are often remained at the surface of sand bed forming a filter cake or surface mat (McDowell-Boyer *et al.*, 1986). Types of particles contained in the filter cake influence greatly its properties such as hydraulic conductivity, porosity, compressibility and the capacity to restrain other particles (Weber-Shirk and Dick, 1997). This particle deposition at the surface leads to a significant decrease of the hydraulic conductivity of the filter.

Straining occurs in constriction when the particles are small enough to penetrate the porous media but too large to pass through the interstices between grains in the sand bed. It mostly takes place at the surface of the filter which contributes to the formation of filter cake since it restricts openings of the sand bed pores (Huisman and Wood, 1974; McDowell-Boyer *et al.*, 1986). Straining is the only one mechanism that is known from the beginning of slow sand filtration establishment. Before the existence of pathogenic bacteria was known, slow sand filtration is only deemed as a strainer for turbidity and suspended solids (Hazen, 1905; Huisman and Wood, 1974). In that period, it was believed that the filter performance depends on the fineness of the strainer which is sand (Hazen, 1905).

Independent of the hydraulic loading rate, straining that is also not influenced by electrostatic interactions. Straining is influenced greatly by the system geometry and the grain shape (Tufenkji *et al.*, 2004). Prediction on the straining potential within porous media based on the system geometry is influenced by the solid or particle diameter (d_p) and the grain mean diameter (d_m) (Herzig *et al.*, 1970; McDowell-Boyer *et al.*, 1986).

Sakthivadivel (1969), as cited by McDowell-Boyer et al. (1986), recommended some values of d_m/d_p to determine the straining potential. Particle penetration to media will not be possible when $d_m/d_p < 10$. In such condition, a filter cake will be formed. For $10 < d_m/d_p < 20$, deposition of particles is expected to occupy > 30% of pore volume and hydraulic conductivity is reduced by a factor of 7-15. Deposition of smaller particles which occupy pore volume is predicted to be only 2-5% if $d_m/d_p > 20$. If the ratios of grain diameter and particle diameter are ranging from $d_m/d_p < 10$ to $d_m/d_p > 20$, the constriction is blocked by larger particles. These larger particles act as strainers for smaller particles. In this case, an effective particle removal by a combination of surface and straining filtration can be achieved (McDowell-Boyer *et al.*, 1986). Sherard *et al.* (1984) conducted an experiment in geotechnical filter materials using fine and coarse media. Sherard *et al.* (1984) found out that there was no penetration of finer sand into the coarser if $d_{c,15}/d_{f,85} < 9$. The term $d_{c,15}$ represents the coarse grain size corresponds to 15 % finer by weight and $d_{f,85}$ represents the fine grain size corresponds to 85 % finer by weight.

Herzig *et al.* (1970) proposed a threshold value for d_p/d_m by considering a triangular constriction composed by three tangent spherical grains (see Figure 12). If the value of d_p/d_m is higher than this threshold, the particles cannot penetrate through the constriction. The threshold values vary depending on the amount of the particle at the constriction site. The limit values of d_p/d_m are 0.154, 0.10 and 0.082 for one, three and four particles respectively. When the constriction is clogged due to the subsequent blockage of particles in each crevice, removal of microorganisms by straining is possible. Dullemont *et al.* (2006) proved that by the existence of *Schmutzdecke*, *E.coli* removal was 2 $\log_{10}$ higher due to the straining mechanisms.

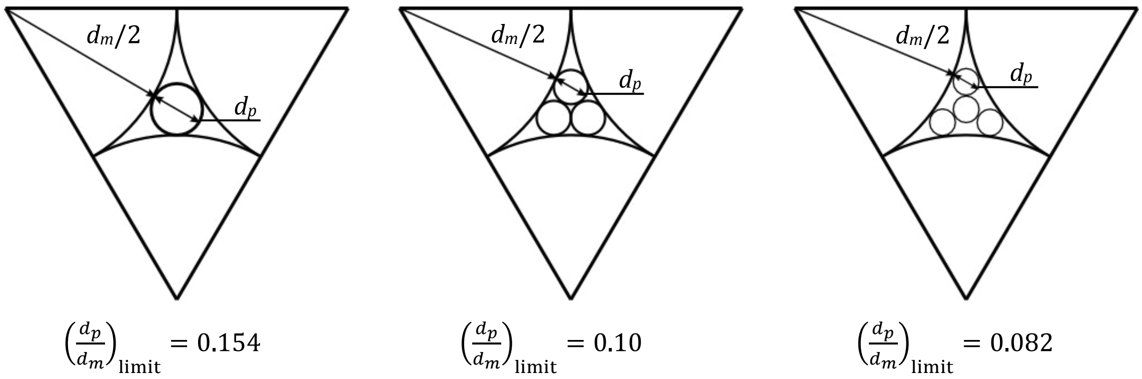


Figure 12. Straining in a triangular constriction (Herzig *et al.*, 1970)

Another relevant variable contributing to the straining potential is media grain shape. Variation of grain shapes leads to the increase of pore size distribution (Tufenkji *et al.*, 2004). Crucial aspect of straining by irregular shape of grains is the existence of very small pore throats which allow capture and storage of broader range of particle sizes including colloids (Barton and Buchberger, 2007).

The size of colloids in suspension is much smaller compared to the media grain size. Removal by straining may occur in such condition, but this removal is not significant. Percentage of mass retention by straining is higher for the larger colloid or for the smaller grain (Bradford *et al.*, 2003). For colloid straining, Bradford *et al.* proposed a value of 0.002 for d_p/d_m. However, Xu *et al.* (2006) found out that the straining rates will increase above the d_p/d_m of 0.008.

Due to its size, colloids removal is dominated by physical-chemical mechanism or attachment through a collision with the collector (Bradford *et al.*, 2002; Xu *et al.*, 2006) and securing colloids to the collector's surface (Ives, 1987). McDowell-Boyer *et al.* (1986) proposed a threshold value for colloid removal based on the geometry of the colloid and sand grain. Ratio of media grain size and colloid or d_m/d_p should be > 1000 in order to enable the attachment of colloid.

When characterizing the transport phenomena in porous media, there is a variable to consider. This variable is specific surface area of sand A_s which can be related to hydraulic conductivity (Koponen *et al.*, 1997; Carrier III, 2003). This parameter can have an influence to the removal mechanisms (Langenbach, 2010). Specific surface area of sand is the total interstitial surface area of the voids and pores per unit bulk volume (Bear, 1988). The A_s is influenced by the specific diameter of sand grains d_s and porosity. It has the unit of m^2/m^3 and can be approximated by the following formula (Bear, 1988; Langenbach, 2010):

$$A_s = \frac{6}{d_s}(1-n) \tag{20}$$

Value of d_s in mm depends on the d_{10} and C_u given by (Huisman and Wood, 1974):

$$d_s = d_{10}(1 + logC_u) \tag{21}$$

Total sand surface area A_T where the water has passed within the inner column diameter D and bed depth L can be calculated by (Langenbach, 2010):

$$A_T = A_s \frac{\pi \cdot D^2}{4} L \tag{22}$$

2.5.2 Attachment Mechanisms

The purpose of filtration is to separate the solids from the suspension. Therefore, suspended solids which have made contact with grains need to be attached to the collectors. Suspended solids can be detained at constriction due to the axial pressure of the water which holds on the particles opposing the opening of pores. Friction forces the particles to stop and remain in a crevice. Attachment process of particles to the grains is influenced by not only various chemical-colloidal interactions but also the existence of supporting forces or interactions between particles and grain surface (Elimelech and O'Melia, 1990b). The dominant supporting forces are van der Waals forces and electrical forces (Zamani and Maini, 2009). Van der Waals forces are always attractive while electrical forces can be either attractive or repulsive depending on the physicochemical conditions of the suspension. Derjaguin and Landau (1941) stated that these forces are a function of the distance between the two masses. Thus, the attachment process depends significantly on the distance between the particles and the sand grain surface (Herzig *et al.*, 1970; Huisman and Wood, 1974). If the distance is high, the total energy of interaction is very small that it can be neglected (Hamaker, 1937). According to Zamani and Maini, these supporting forces will be significant if the distance between the two masses is below 100 nm.

Electrostatic forces or interactions which are dominant in the attachment mechanism occurs not only due to the short distance between a particle and a sand grain but also due to the opposite electrical charges (Huisman and Wood, 1974; McDowell-Boyer *et al.*, 1986). Opposite electrical charges of a particle and a grain may lead into attraction force, in contrary repulsion force is originated from interaction between two particles having the same charge. Electrostatic character of particles is also affected by the chemistry of fluid (Elimelech and O'Melia, 1990b; Redman *et al.*, 1997). In this study, quartz sand was selected as filter media. According to Huisman and Wood (1974) quartz sand has a negative charge. The selected surrogate material which was quartz powder certainly has the same charge as the filter media. Therefore, this type of attachment mechanisms is not significant during the filtration process except the grain sand took some positively charged particles presence in tap water and this double layer lead into the attraction of quartz powder. Moreover, related to Bradford *et al.* (2002), since the size of Millisil is larger than the size of colloid, it can be predicted that the dominant removal mechanisms are by sedimentation and interception.

Out of the van der Waals and electrostatic forces, there are some forces involved in the mechanism of attachment. Those forces are steric forces adherence, hydration (structural) forces and hydrophobic forces (Huisman and Wood, 1974; Elimelech and O'Melia, 1990b; Bradford *et al.*, 2002; Binnie and Kimber, 2013). Interaction of two surfaces due to steric forces takes place when polymers are adsorbed onto the interfaces of interacting particles and surfaces (Elimelech and O'Melia, 1990b).

Adhesion occur due to the formation of slimy material (zoogloea) during the ripening period by the bacteria and other microorganisms that are deposited on the filter surface (Huisman and Wood, 1974). This zoogloea produces a sticky gelatinous film which allows some particles from the raw water to adhere when they are brought into contact through one of the transport processes.

According to Liang *et al.* (2007) hydration forces refer to solvation forces when the solvent is water. Hydration forces start to occur when the distance of two particles is closer than a few nanometers. Geometric constrain and attractive interaction between the particle and liquid molecules generate the solvation forces. These forces are influenced by the chemical and physical properties of the particles and the medium.

Hydrophobic forces occur when two hydrophobic particles are attracted each other and some water molecules are trapped in narrow space between them. A hydrophobic particle does not have any hydrogen-bonding sites. In contrary, water molecules tend to form hydrogen-bonding clusters. In the case of trapped water molecules, formation of hydrogen-bonding clusters are restricted by the hydrophobic particles. Hence water molecules will migrate to the bulk water where the formation of hydrogen-bonding clusters is not restricted. As a consequence, an attractive force between the two hydrophobic particles rises allowing the two particles to attach one another (Liang *et al.*, 2007).

Other factors controlling the kinetics of particles attachment are the hydraulic loading rate and the fixation to the grain surface (Bradford *et al.*, 2002). The efficiency of collector also has an influence to the particles attachment. This efficiency is independent of the particle size but it is affected by diffusion, interception and gravitational sedimentation (Elimelech and O’Melia, 1990a; Logan *et al.*, 1995).

2.6 Settling Velocity of Suspended Solids and Stokes' Law

Characteristics of suspended solids influence the removal mechanism in the system, especially by sedimentation. Efficiency of sedimentation is affected by settling velocity of the particles. Camenen (2007) and Binnie and Kimber (2013) listed several parameters which influence the settling velocity such as shape, roundness, size and density of particles. When only gravitational force is participated, , a particle having greater density than water will be sedimented (Binnie and Kimber, 2013). At the beginning of the settlement, gravitational force accelerates the process before then its velocity becomes gradually constant due to the resistance of water. This settling velocity v_s is given by (Rubey, 1933; Binnie and Kimber, 2013):

$$v_s = \left[\frac{4 \cdot g \cdot (\rho_1 - \rho) \cdot D}{3 \cdot C_D \cdot \rho}\right]^{0.5} \tag{23}$$

where g is acceleration due to gravity; ρ_1 is the density of particle; ρ is the density of water; D is the particle diameter; C_D is the drag coefficient.

Drag coefficient C_D is influenced by the Re where it will be increased along with the decrease of Re (Camenen, 2007). In laminar flow, C_D is influenced by the Re where it will be increased along with the decrease of Re. The relation between C_D and Re is formulated as follows (Johnson *et al.*, 1996):

$$C_D = \frac{24}{Re} \tag{24}$$

By replacing the Re in Equation 24 with the one from Equation 1 followed by combining the Equation 23 and 24, the settling velocity in laminar flow known as Stokes' law can be determined as follows (Rubey, 1933; Binnie and Kimber, 2013):

$$v_s = \frac{1}{18} \cdot g \cdot \frac{(\rho_1 - \rho)}{\eta} \cdot D^2 \tag{25}$$

Removal by sedimentation occurs if settling velocity is equal or greater than the surface loading rate or in this case is hydraulic loading rate (Huisman und Wood 1974).

2.7 Operating Variables Influencing Filter Performance

The fundamental purpose of designing a slow sand filtration is to have a filter which can maintain not only the high quality of treated water but also the operation period.

Performance of slow sand filtration depends on the operating variables. These operating variables are the matters of choice although some recommended values for them have been established (see Table 1). In the following sections, influence of each operating variables, i.e. grain size distribution, hydraulic loading rate, filter bed depth and supernatant layer, on the filter performance are presented.

2.7.1 Grain Size Distribution

Sand as the filter media is the critical part of slow sand filtration. Huisman and Wood (1974) and Rolland *et al.* (2009) agree that grain size distribution of media is one of the most important operating variables which ensure the effluent quality. The grain size distribution is represented by effective size d_{10} and uniformity coefficient C_u (Crites and Tchnobanoglous, 1998) (see also Section 2.3). In the water filtration studies, d_{10} is a basis to determine the diameter of filter column. The wall effect can be neglected as far as the ratio of the diameter of filter column to the d_{10} is higher than 50 (Lang *et al.*, 1993).

The d_{10} and C_u are very essential because both influence the internal characteristics of the filter media such as its porosity and hydraulic conductivity (Clark *et al.*, 2012). These characteristics affect the filter performance, particularly to the impurities penetration to a depth where the surface scraping is not sufficient to clean the filter (Huisman and Wood, 1974; Ellis and Aydin, 1995).

According to the recommendation values of grain size distribution on the design criteria of slow sand filtration, fine media is preferably chosen but it does not necessarily need to be uniform. Huisman and Wood (1974) collected the data around Europe and found out that mostly the slow sand filters were designed with the d_{10} of 0.15-0.35 mm and C_u of below 3. Small value of d_{10} will ensure the good effluent quality (Visscher, 1990) and such degree of C_u is needed to provide regular pore sizes and sufficient porosity (Huisman and Wood, 1974).

In 1996, van der Hoek, J. P. *et al.* investigated the influence of grain size in the filter performance. They compared two media with d_{10} of 0.19 mm and 0.25 mm. The result showed that the smaller grain size produced a slightly better efficiency although the filter run time is shorter. The research conducted by Rolland *et al.* (2009) revealed similar conclusion as van der Hoek, J. P. *et al.*. Rolland *et al.* investigated the grain size effect to the hydraulic and biological behaviors. The fine sand with d_{10} of 0.33 mm and C_u of 2.57 and coarse sand with d_{10} of 0.8 and C_u of 3 were compared. Biological behaviors linked to the treatment efficiency showed that fine grain performed significantly better than the coarse sand.

Interesting results were reported by Bellamy *et al.* (1985a). They investigated the influences of some operating variables on the slow sand filtration performance. One of the operating variables tested was the grain size distribution. It was found out that filter performance raises along with the decrease in d_{10}. This observation was in agreement with the result of van der Hoek, J. P. *et al.*. However, the removal of standard plate count bacteria reached 99.70 % for a filter with d_{10} of 0.62 mm while for finer media with d_{10} of 0.29 mm achieved 99.90 %. The filter with coarse sand was also able to reach high removal efficiency of Giardia cysts and total coliform bacteria. From this result, it was concluded that the argument from Huisman and Wood, Visscher and Barrett *et al.* (see Table 4) to use fine sand cannot be considered as a general rule.

In addition to the conclusion of Bellamy *et al.* (1985a) on d_{10}, Muhammad *et al.* (1996) figured out that coarser sand up to 0.45 mm with C_u of 2 could provide satisfactory removal level of fecal coliform and total coliform. In regard to the turbidity, Muhammad *et al.* observed a removal efficiency of higher than 96 % for filters with d_{10} of 0.20 mm and 0.45 mm. Confirming this result, Langenbach (2010) did not detect significant impact from the variation of d_{10} in the range of 0.25–0.8 mm with C_u of 1.6 on the total suspended solids removal.

Related to the filter run time, Muhammad *et al.* (1996) and Elisson (2002) had the same results where the sand with lower d_{10} will have shorter filter run time compared to the coarser sand. It is because a slow sand filter with excessive fine grains lacks adequate pore sizes.

Focusing on the influence of C_u, Di Bernardo and Escobar Rivera (1996) variated the C_u from 2.2 to 4.3. In terms of the percent removal of apparent colour, turbidity, total iron and manganese, faecal coliform and heterotropic bacteria colonies, it was found that higher C_u provides better effluent quality. Moreover, the filter run time will be longer although the particles may penetrate deeper in the filter with higher C_u. Confirming the result of Di Bernardo and Escobar Rivera particularly on the filter run time, Zipf *et al.* (2016) found out that lower C_u leads into shorter filtration career. However, a clear comparison could not be achieved because the two media had a different characteristic. One media had a d_{10} of 0.49 mm and a C_u of 2 while another media had a d_{10} of 0.17 and a C_u of 5.

On the contrary to the results of Di Bernardo and Escobar Rivera and Zipf *et al.*, Langenbach (2010) stated that higher C_u will lead into a shorter filter run time. It is because higher C_u causes a lower porosity of the filter bed. In ungraded sand, grain sizes are widely varied and the finer ones may fill in the interspaces between coarser grains (Elisson, 2002). Therefore, the filter will be easier to clog with a higher C_u.

2.7.2 Hydraulic Loading Rate

Preference on the hydraulic loading rate that will be applied in the filter operation greatly affects the surface area of slow sand filter required (Hazen, 1905). Equation 3 shows that hydraulic loading rate is inversely proportional to the surface area of filter. This means in order to fulfill the demand, if the filter is operated under a high hydraulic loading rate, a filter with smaller surface area is sufficient. However, high hydraulic loading rate does not only lead to a rapid clogging thus requires more often scraping, but also to a deeper penetration of particulate impurities (Hazen, 1905; Huisman and Wood, 1974). Values for hydraulic loading rate recommended by Huisman and Wood (1974), Visscher (1990) and Barrett *et al.* (1991) are in the range of 0.04-0.40 m/h (see Table 1). These low hydraulic loading rates are recommended to ensure satisfactorily effluent quality.

Di Bernardo and Escobar Rivera (1996) confirmed that slow sand filter performed better under low hydraulic loading rate. In their study, investigation on the influence of three hydraulic loading rates i.e. 0.10 m/h, 0.20 m/h and 0.25 m/h on the turbidity removal was conducted. It was proved that higher hydraulic loading rate does not only produce a worse effluent quality in terms of turbidity but also a shorter filter run time.

The conclusion of Di Bernardo and Escobar Rivera (1996) on the removal efficiency and filter run time was approved by Tyagi *et al.* (2009). During their research, Tyagi *et al.* (2009) observed the development of head loss from a filter operated under three different hydraulic loading rates i.e. 0.14 m/h, 0.19 m/h and 0.26 m/h. The results showed that a rapid head loss development occurred in the filter with the hydraulic loading rate of 0.26 m/h. This rapid rate of head loss increase caused shortest filter run time. Under the hydraulic loading rate of 0.26 m/h, the percentage of suspended solids and BOD removal of the filter was the lowest.

Influence of the hydraulic loading rate on the slow sand filtration performance was also investigated by Bellamy *et al.* (1985b) particularly in term of effluent quality. Using three identical filter columns packed with d_{10} of 0.28 mm and C_u of 1.46, they compared three different hydraulic loading rates of 0.04 m/h, 0.12 m/h and 0.40 m/h. Percent removal of Giardia cysts, bacteria, turbidity and particles. was used to determine the effect of different hydraulic loading rate. Findings showed that slow sand filtration performance declined with the increase of hydraulic loading rate. Nevertheless, at the rate of 0.4 m/h removal of Giardia cysts and coliform bacteria were still above 99%.

The results from Bellamy *et al.* (1985b) were strengthened by the findings of Muhammad *et al.* (1996). By testing three hydraulic loading rates of 0.10 m/h, 0.20 m/h and 0.30 m/h, Muhammad *et al.* (1996) found out that the bacteriological quality in the outlet does not decline significantly with the increase of hydraulic loading rate. The percent removal of turbidity and color declined considerably with increase of hydraulic loading rate but the effluent quality was still good. From this study, it can be concluded that a hydraulic loading rate which is higher than the conventional value of 0.10 m/h (Ellis and Wood, 1985), can be employed when the raw water quality is good, although the high hydraulic loading rate may cause frequent scraping. Cleasby (1991) as cited by Logsdon *et al.* (2002) recommended a good quality raw water for slow sand filtration as follows:

a. The turbidity is low (< 5 NTU).

b. Iron concentration is < 0.3 mg/L.

c. Manganese concentration is < 0.05 mg/L.

d. Algae bloom is very low and chlorophyll *a* is < 0.05 µg/L.

Langenbach (2010) rejected the conclusion of Muhammad *et al.* (1996) especially on the physical removal. Langenbach (2010) reported that hydraulic loading rate did not show a significant impact on the TSS removal. In the investigation, Langenbach (2010) employed six filter columns. These columns were filled up with sand which had varied d_{10} from 0.23 mm to 0.82 mm and C_u ranged from 1.36 to 4.91. The test was divided into three phases. In phase I, hydraulic loading rate was set under 0.05 m/h then 0.10 m/h and 0.20 m/h for phase II and phase III respectively. Percent removal of TSS ranged from 70-84% and did not influence by the different hydraulic loading rates. The reason for this was because the mechanism on TSS removal is mechanical straining which takes place mostly in the filter cake. This means after the ripening period, grain size distribution and hydraulic loading rate do not play significant role anymore.

During the filter operation, avoiding frequent rate changing is the most suitable way to enhance the slow sand filtration performance (Logsdon *et al.*, 2002). In the case of declining rate, Visscher (1990) stated that it may cause significant fluctuation in the thickness of supernatant layer which later leads into larger filter area or higher filter box requirements to be able producing the same amount of output as in the constant rate.

2.7.3 Sand Bed Depth

Collins *et al.* (1991) reported that slow sand filtration performance is a function of the maturation degree and the depth of sand bed as filter media. According to the Section 2.7.2, a high hydraulic loading rate may decline the performance of slow sand filtration. This decline can be diminished by increasing the thickness of sand bed. Determination of filter bed thickness is influenced by the removal mechanisms within the media and the consideration of re-sanding. Higher sand bed depth allows scraping and cleaning during maintenance process therefore delaying the re-sanding (Clark *et al.*, 2012).

Visscher (1990) suggests a minimum depth of 500-600 mm and a minimum of 600 mm should be taken if slow sand filtration is a single treatment. According to Huisman and Wood (1974), thickness of sand bed in slow sand filtration must be at least 700 mm due to the purification zones. Bacteria purification occurs usually in the top 300-400 mm of sand bed and below this layer lies the mineral oxidation zone with the thickness of 400-500 mm. Deposition of suspended solids and colloidal matter mostly happens at the surface of sand bed which can be removed by scraping off 10-20 mm of the top layer (Huisman and Wood, 1974; Weber-Shirk and Dick, 1997).

Datta and Chaudhuri (1991) found out that the inactivation of bacteria mostly occurs at the top layer of the bed between 100-250 mm from the total of 1000 mm depth. Ellis and Aydin (1995) investigated the removal of solids and particulate organic carbon through the be depth of 1200 mm. They observed that solids content and particulate organic carbon decreased rapidly to a depth of 300 mm. Both studies by Datta and Chaudhuri (1991) and Ellis and Aydin (1995) confirmed that the purification mechanisms take place mostly at the top of sand layer, ranging from one tenth to one fourth of the total bed depth.

Bellamy *et al.* (1985a) observed that by increasing the bed depth, the percentage of remaining coliforms decreases. However, by lowering the bed depth up to 480 mm does not seriously impair the filtration performance where 95% of coliform removals could still be achieved. Muhammad *et al.* (1996) approved the conclusion of Bellamy *et al.* by investigating the influence of sand thickness of 400 mm and 730 mm on the effectiveness of the filter. The result showed that the thickness of sand bed is not the key parameter for bacteria removal. Related to the turbidity and color removal, filter column with thicker bed depth performed slightly better. Overall, a sand bed with 400 mm can still provide a good quality of effluent.

Nancy *et al.* (2014) confirmed the results of Bellamy *et al.* (1985a), Datta and Chaudhuri (1991), Ellis and Aydin (1995) and Muhammad *et al.* (1996) by testing three various bed depth of 500 mm, 700mm and 1000 mm respectively. Nancy *et al.* (2014) observed that turbidity and TSS value in the effluent decreased with the increase of bed depth. Efficiency of bacteria removal, however, did not significantly affected by the decrease of bed depth. Those facts prove that recommended design criteria for bed thickness are rather for the purpose of prolonging the re-sanding period than ensuring the filter performance.

Filter bed depth may alter due to the compaction process during the filter operation (Kandra *et al.*, 2014). By the compaction, porosity of the sand bed is smaller thus the hydraulic conductivity decreases. Process of compaction in sand bed means reducing the air fraction or available void and modifying the grains arrangement (Bardet, 1997). Modification of initial and final hydraulic conductivity can be related to compaction where it contributes to the reduction of filter capacity to transport water (Hatt *et al.*, 2008).

2.7.4 Supernatant Layer

Purification mechanism in both inlet and outlet controlled systems is started from the supernatant layer where sedimentation may take place (van Dijk and Oomen, 1978; Sánchez *et al.*, 2006). Supernatant layer above the filter media has two major function, which are (Huisman and Wood, 1974; van Dijk and Oomen, 1978; Visscher, 1990):

a. providing a detention period for the raw water, during which some purification mechanisms occur such as sedimentation, particle agglomeration and oxidation;

b. providing the head pressure for the water to flow through the sand bed.

Level of supernatant layer is influenced by the control system (see Figure 4 and Figure 5) of the hydraulic loading rate. By using inlet controlled system, level of supernatant layer is higher along with the increase of head loss. Meanwhile, in the outlet controlled system, supernatant layer can be kept at constant level.

According to the studies of van Dijk and Oomen (1978) and Abudi (2011), level of supernatant layer has some influences to the slow sand filtration performance. van Dijk and Oomen (1978) stated that to maintain constant water height under the normal operation condition is preferable. Under constant supernatant layer, the risk of disturbing the filter cake is reduced, floating impurities can be taken through the fixed scum outlets and deep penetration of sunlight can be prevented. Sunlight penetration may stimulate plants growth in the sand surface (Huisman and Wood, 1974). Abudi (2011) observed that a constant water depth could prevent the change of bio zone and removal efficiency. The increase on the level of supernatant layer, up to higher than 500 mm, will lead into lower oxygen diffusion and thinner biological layer. Then, oxidation and metabolism of microorganisms in the biological zone may decrease. If this occurs, the layer will no longer be functioning and at the worst case, it might become an ineffective filter.

In order to find out the influence of constant supernatant layer, Di Bernardo and Alcócer Carrasco, N. E. (1996) compared two filter columns. The first filter was operated with constant hydraulic loading rate and constant supernatant layer. The second filter was employed with decreasing supernatant layer. Decreasing level means that the water was allowed to flow from maximum level to the minimum level above the sand bed in the filter box. Analysis of performance was based on the effluent quality and filter run times. According to the findings, the impact of supernatant layer whether constant or decreasing on the filter performance was insignificant.

3 Research Questions and Objectives

Previous findings in the influence of operating variables presented in Section 2.7 may imply that the recommended design criteria are rather conservative. Applying the recommended values does not necessarily ensure an excellent slow sand filtration performance. As a matter of choice, the decision on the design of slow sand filtration cannot be dependent on the recommended values (see Table 1) only. Unfortunately, most of the previous tests were conducted with different filter configurations. As an example the study of Zipf *et al.* (2016) who compared fine and coarse media with different values of C_u. This setting may complicate the conclusion of which operating variables of the design criteria dominate the effect to the slow sand filtration performance. Moreover, the influence of every operating variable on the removal mechanism is still rare to be found in the literature. Optimization and wider application of slow sand filtration technology may be restricted due to the existence of this gap. Therefore, the main purpose of this study was to optimize the design recommendation of slow sand filtration by understanding the influence of each operating variable independently on the suspended solids removal mechanisms. There were two reasons behind the selection of suspended solids removal as a focus. The first was because suspended solid is a significant pollutant in the water and it may affect the disinfection process (see Section 2.1). The second was because its physical removal is a fundamental mechanism in slow sand filtration (see Section 2.5). Along with the main purpose, an attention was also given to the method of increasing filter run time and hydraulic loading rate.

In order to achieve the main purpose of this research, some specific objectives along with the research questions were defined as follows:

1. to identify the effect of operating variables, specifically d_{10}, C_u and high hydraulic loading rate on the removal efficiency.

   How is the influence of each operating variable on the removal efficiency of suspended solids?

   Is grain size distribution represented by d_{10} and C_u the dominant factor which influences the removal efficiency?

   Does coarse sand produce a low filtrate quality?

   Does high hydraulic loading rate deteriorate the removal efficiency significantly?

2. to find out the influence of d_{10}, C_u, hydraulic loading rate and bed depth on the solids penetration and dominant removal mechanisms within the filter bed.

   How is the influence of each operating variable on the solids penetration in filter bed?

   How does each operating variable influence the dominant removal mechanism?

   How does suspended solids deposition influence the clogging period?

3. to identify the clogging period by observing the development of hydraulic conductivity and head loss.

   How is the influence of each operating variable on the progressive head loss?

4. to evaluate the method for prolonging the filter run time by adding protection layer.

   Is the method of Mälzer and Gimbel (2006) on the addition of protection layer a suitable approach to prolong the filter run time?

5. to investigate the method for increasing the hydraulic loading rate.

   Are the recommended values of hydraulic loading rate plausible to be followed?

The approach to achieve the objectives was by investigating the influence of each operating variable systematically. A systematic scientific investigation allows the operating variables to be investigated independently. The experimental approach used in this study is still limited in the literature making it as a great challenge in the study.

4 Materials and Methods

4.1 Overview of Experimental Setup

Due to the limited literature on the experimental approach, many parts of the experimental set-up were not standardized. Therefore, the experimental works were divided into three major phases i.e. pre-experiment, Phase I and Phase II.

Pre-experiment phase was conducted to set up the materials and procedure. Grain size distribution of media, characteristic of media in regard to specific gravity, methods of filter construction, potential surrogate material and suitable operation mode related to the supernatant layer were determined in this phase. A part of the tests especially on the setup of varied grain size distribution represented by d_{10} and C_u provided several results which served as a presumptive basis of the filter performance in Phase I and Phase II. The trial of the experimental setup was very important because methods of filter run, hydraulic conductivity measurement, sampling and evaluation of filter performance for Phase I and Phase II were tested here. In addition, the influence of protection layer was also figured out.

Phase I focused on the investigation of the influence of operating variables on the suspended solids removal. The operating variables that were tested consisted of d_{10} and C_u of media and high hydraulic loading rate. Filter columns were constructed from Plexiglass with the diameter of 125 mm and height of 1200 mm. A set of filter columns for the test of each operating variable was replicated two to three times in order to obtain the reliable data. In Phase I, the removal mechanisms of slow sand filtration remained into a black box because the evaluation of filter performance was only based on its ability to remove the suspended solids. Two important parameters used in the evaluation of filer performance were turbidity and TSS. Development of hydraulic conductivity and head loss was also observed to monitor the clogging period.

In Phase II, the focus was divided into two essential parts. The first part was similar to the focus of Phase I, investigating the performance of filter especially on solids removal. The second part was on the determination of solids penetration in the filter bed to identify the removal mechanism. Observation on the penetration of solids is important because it also relates to the filter maintenance. Deeper solids penetration may lead to the failure of surface scraping. If the solids penetrate too deep in the filter bed, the risk of changing the whole filter media was higher.

There were three independent variables tested in Phase II, i.e. d_{10}, C_u and hydraulic loading rate. During the tests in this phase, filter columns with diameter of 60 mm were used. Analysis on the solids penetration was conducted adapting the method of Ellis and Aydin (1995). At the beginning, every 10 mm of filter bed was scraped carefully using a small long scoop. Each sand sample was placed in an Erlenmeyer flask. Then each sand sample was diluted by adding 100 mL of distilled water. Every diluted sample was shaken for 40 minutes using a flask shaker operated at 100 rpm. Afterwards, the diluted sample was rested for 5 minutes allowing the sand to settle down. The supernatant containing the suspended solids was decanted for the turbidity measurement. By investigating the solids penetration in the bed depth, influence of operating variables i.e. grain size distribution, hydraulic loading rate and bed depth on the dominant removal mechanisms (see Figure 11) could be identified. Investigation on the adequacy of adding protection layer to prolong the filter run time was also conducted within the Phase II. Based on the analysis of solids penetration, the function of gravel layer above the sand bed could be verified.

In the entire experimental phases, a total of 10 filter columns were built for the pre-experiment phase. The tests in Phase I and Phase II involved in total 18 and 13 filter columns respectively. Table 3 presents the list of each test with the amount and diameter of filter columns.

Table 3. Overview of constructed filter columns for each test

Test	Grain Size Distribution of Filter Media		Porosity n	Empirical Hydraulic Conductivity (m/s)		
	d_{10} (mm)	C_u		Beyer k_B	Hazen k_H	Kozeny-Carman k_{KC}
Pre-experiment						
Supernatant Layer:						
Constant-Filter 1	0.26	2.5	0.33	9.16×10^{-4}	6.76×10^{-4}	2.14×10^{-4}
Constant-Filter 2	0.26	2.5	0.33	9.16×10^{-4}	6.76×10^{-4}	2.14×10^{-4}
Decreasing-Filter 1	0.26	2.5	0.33	9.16×10^{-4}	6.76×10^{-4}	2.14×10^{-4}
Decreasing-Filter 2	0.26	2.5	0.33	9.16×10^{-4}	6.76×10^{-4}	2.14×10^{-4}
Setup of d_{10}:						
Filter 1	0.075	2.5	0.38	7.62×10^{-5}	-	2.83×10^{-5}
Filter 2	0.50	2.5	0.35	3.39×10^{-3}	2.80×10^{-3}	9.59×10^{-4}
Setup of C_u:						
Filter 1	0.15	2.5	-	3.05×10^{-4}	-	-
Filter 2	0.15	5	-	2.65×10^{-4}	-	-

Table 3. (continued)

Test	Grain Size Distribution of Filter Media		Porosity n	Empirical Hydraulic Conductivity (m/s)		
	d_{10} (mm)	C_u		Beyer k_B	Hazen k_H	Kozeny-Carman k_{KC}
Pre-experiment						
Protection Layer:						
WOPL Filter	0.20	1.74	-	5.79×10^{-4}	-	-
WPL Filter	0.20	1.74	-	5.79×10^{-4}	-	-
Phase I						
Solids Removal in Varied d_{10}:						
Set 1						
Filter 1	0.075	2.5	0.42	7.62×10^{-5}	-	3.86×10^{-5}
Filter 2	0.15	2.5	0.41	3.05×10^{-4}	2.38×10^{-4}	7.85×10^{-5}
Filter 3	0.26	2.5	0.36	9.16×10^{-4}	7.90×10^{-4}	2.81×10^{-4}
Filter 4	0.40	2.5	0.35	2.17×10^{-3}	1.62×10^{-3}	5.14×10^{-4}
Filter 5	0.50	2.5	0.34	3.39×10^{-3}	2.62×10^{-3}	8.56×10^{-4}
Set 2						
Filter 1	0.15	2.5	0.34	3.05×10^{-4}	3.26×10^{-4}	1.42×10^{-4}
Filter 2	0.26	2.5	0.33	9.16×10^{-4}	6.71×10^{-4}	2.11×10^{-4}
Filter 3	0.40	2.5	0.33	2.17×10^{-3}	1.75×10^{-3}	5.88×10^{-4}
Filter 4	0.50	2.5	0.32	3.39×10^{-3}	2.37×10^{-3}	7.52×10^{-4}
Solids Removal in Varied C_u:						
Set A						
Filter 1	0.26	2.5	0.32	9.16×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 2	0.26	3	0.32	8.84×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 3	0.26	5	0.32	7.96×10^{-4}	6.19×10^{-4}	1.91×10^{-4}

Table 3. (continued)

Test	Grain Size Distribution of Filter Media		Porosity n	Empirical Hydraulic Conductivity (m/s)		
	d_{10} (mm)	C_u		Beyer k_B	Hazen k_H	Kozeny-Carman k_{KC}
Phase I						
Set B						
Filter 1	0.26	2.5	0.32	9.16×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 2	0.26	3	0.32	8.84×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 3	0.26	5	0.31	7.96×10^{-4}	5.81×10^{-4}	1.86×10^{-4}
Set C						
Filter 1	0.26	2.5	0.32	9.16×10^{-4}	6.30×10^{-4}	1.91×10^{-4}
Filter 2	0.26	3	0.32	8.84×10^{-4}	6.21×10^{-4}	1.68×10^{-4}
Filter 3	0.26	5	0.29	7.96×10^{-4}	5.31×10^{-4}	1.47×10^{-4}
Solids Removal in High Hydraulic Loading Rate*:						
Set A						
Filter 1	0.26	2.5	0.32	9.16×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 2	0.26	3	0.32	8.84×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 3	0.26	5	0.32	7.96×10^{-4}	6.19×10^{-4}	1.91×10^{-4}
Set B						
Filter 1	0.26	2.5	0.32	9.16×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 2	0.26	3	0.32	8.84×10^{-4}	6.30×10^{-4}	1.90×10^{-4}
Filter 3	0.26	5	0.31	7.96×10^{-4}	5.81×10^{-4}	1.86×10^{-4}
Set C						
Filter 1	0.26	2.5	0.32	9.16×10^{-4}	6.30×10^{-4}	1.91×10^{-4}
Filter 2	0.26	3	0.32	8.84×10^{-4}	6.21×10^{-4}	1.68×10^{-4}
Filter 3	0.26	5	0.29	7.96×10^{-4}	5.31×10^{-4}	1.47×10^{-4}

Table 3. (continued)

Test	Grain Size Distribution of Filter Media		Porosity n	Empirical Hydraulic Conductivity (m/s)		
	d_{10} (mm)	C_u		Beyer k_B	Hazen k_H	Kozeny-Carman k_{KC}
			Phase II			
Solids Removal and Penetration in Varied d_{10}:						
Filter 1	0.075	2.5	0.33	7.62×10^{-5}	-	1.84×10^{-5}
Filter 2	0.26	2.5	0.35	9.16×10^{-4}	7.49×10^{-4}	2.55×10^{-4}
Filter 3	0.50	2.5	0.34	3.39×10^{-3}	2.58×10^{-3}	8.34×10^{-4}
Filter 4	0.70	2.5	0.36	-	5.73×10^{-3}	2.04×10^{-3}
Filter 5	0.90	2.5	0.35	-	9.05×10^{-3}	3.10×10^{-3}
Solids Removal and Penetration in Varied C_u:						
Filter 1	0.26	2.5	0.37	9.16×10^{-4}	8.30×10^{-4}	3.07×10^{-4}
Filter 2	0.26	3	0.33	8.84×10^{-4}	6.76×10^{-4}	2.14×10^{-4}
Filter 3	0.26	7	0.31	7.38×10^{-4}	6.09×10^{-4}	1.81×10^{-4}
Solids Removal and Penetration in Varied Hydraulic Loading Rate*:						
Filter 1-0.08 m/h	0.26	2.5	0.33	9.16×10^{-4}	6.72×10^{-4}	2.12×10^{-4}
Filter 2-0.20 m/h	0.26	2.5	0.37	9.16×10^{-4}	8.30×10^{-4}	3.07×10^{-4}
Filter 3-0.80 m/h	0.26	2.5	0.34	9.16×10^{-4}	7.33×10^{-4}	2.45×10^{-4}
Increasing the Filter Run Time:						
Filter 1-WOPL	0.26	2.5	0.37	9.16×10^{-4}	8.30×10^{-4}	3.07×10^{-4}
Filter 2-WPL	0.26	2.5	0.34	9.16×10^{-4}	7.18×10^{-4}	2.37×10^{-4}

*The test used the same filter columns as in the test of solids removal in varied C_u

**One filter column is from the test of solids removal and penetration in varied C_u

4.2 Pre-Experiment Phase

4.2.1 Filter Media and Determination of Specific Gravity

Quartz sand was the only type of sands tested in the entire experimental phases. The quartz sand was supplied by two companies from Germany, Gebrüder Willersinn GmbH in Ludwigshafen and Friedrich Quarzsandwerke in Rheinhafen. The first supplier also provided the gravels that were used for the supporting and protection layer. The gravel was washed and dried in the laboratory and sieved with two sieve openings. The objective of sieving was to separate the gravel size into coarse (>6.3 mm) and fine (2-6.3 mm) fractions. By using the separate gravel size, construction of supporting layer could be stratified where the coarse gravel was placed under the finer one. This grading allowed the supporting layer to be more stable to hold up the sand bed. The fine gravel was also used as a protection layer, which was installed above the sand bed, for several filter columns.

Fulfilling the requirement of systematic investigation, grain size distribution represented by d_{10} and C_u has to be determined so that at the end the configurations of filter columns can be compared equally. As an example, when the purpose of the test was to identify the influence of the media size on the slow sand filtration performance, then the grain size distributions of media was varied in d_{10} while the C_u was maintained the same (see Figure 13). On the contrary, if the focus was to investigate the influence of the range of media size on the slow sand filtration performance, then the grain size distributions of media was varied in C_u while the d_{10} was maintained the same (see Figure 14). From the grain size distribution graph, the y-axis shows the percentage of finer grain size by weight and the x-axis shows the grain size.

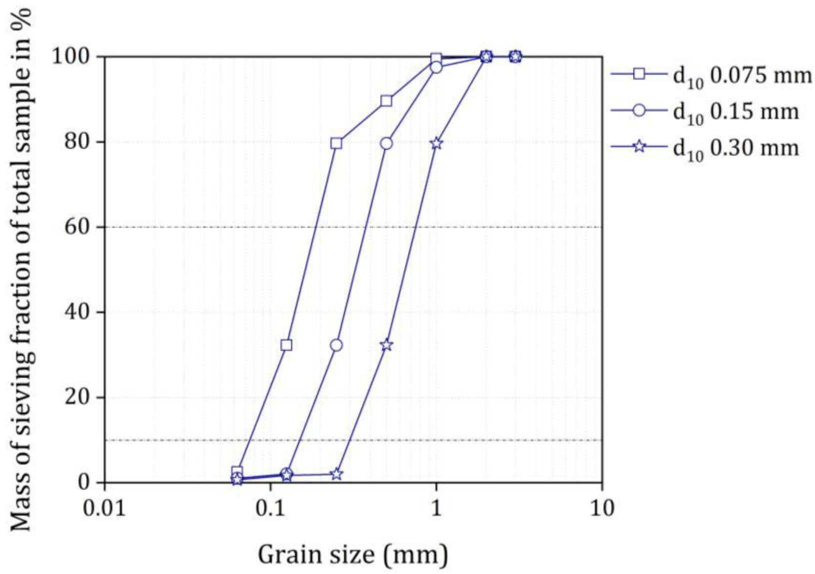


Figure 13. Comparison of grain size distributions with different d_{10} but similar in C_u of 2.5

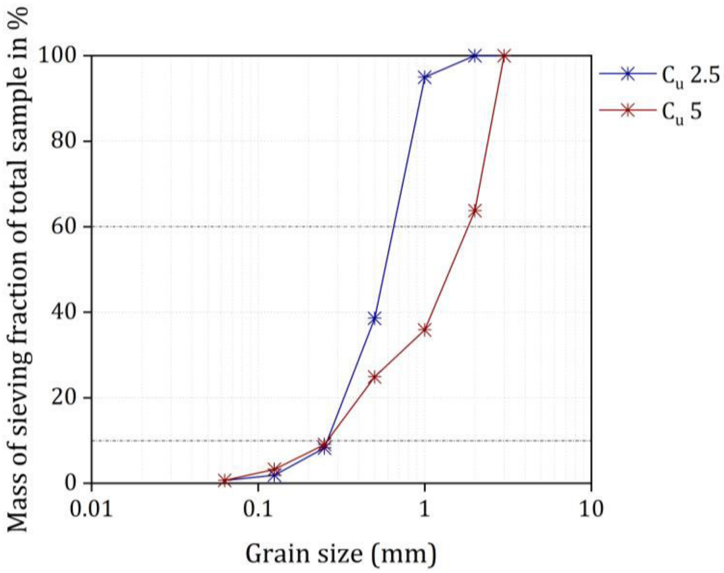


Figure 14. Comparison of grain size distributions with similar d_{10} of 0.26 mm but different C_u

A calculation involving the size of sieve openings has been made so that the desired grain size distribution can be obtained. Since both suppliers were not able to provide the sand with desired grain size distribution as presented in Table 4, they had to be prepared in the laboratory. At the beginning, sand from the supplier should be separated based on the grain size using a sieving machine. Sieving was conducted under the dry method using a stack of sieves with seven to eight different size openings: 3 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm and 0 cm. After that, the sand was remixed based on the grain composition in Table 4. The mixing was done manually using a bucket and a scoop due to the small amount of mass per mixture. A sample of around 250 g of sand was then taken from the new mixture for a sieving analysis. This sieving analysis was to ensure that the sand is well-mixed.

Table 4. Composition of sand fraction of filter media

d_{10} (mm)	C_u	Composition of sand size (%)						
		2-3 mm	1-2 mm	0.5-1 mm	0.25-0.5 mm	0.125-0.250 mm	0.063-0.125 mm	0-0.063 mm
0.075	2.5	0.00	0.50	9.92	9.92	47.37	29.79	2.50
0.15	2.5	0.00	2.45	17.90	47.35	30.26	1.01	1.03
0.15	5	0.00	32.73	17.53	34.17	7.56	7.51	0.50
0.26	2.5	0.00	5.05	56.36	30.33	6.37	1.21	0.68
0.26	3	0.00	25.48	40.87	25.11	3.36	4.50	0.68
0.26	5	0.00	64.39	7.19	19.53	3.71	4.50	0.68
0.26	7	36.25	27.88	10.97	15.83	5.82	2.57	0.68
0.30	2.5	0.00	20.38	47.28	30.32	0.33	1.01	0.68
0.40	2.5	0.00	40.48	45.72	12.25	0.21	1.01	0.33
0.50	2.5	0.00	59.97	30.29	8.54	0.21	0.94	0.05
0.70	2.5	30.73	49.12	19.90	0.25	0.00	0.00	0.00
0.90	2.5	56.38	31.88	11.49	0.25	0.00	0.00	0.00

One of the characteristics of the sand, specific gravity (see Section 2.3), was also determined in the laboratory. Value of void ratio e (see Equation 11) and porosity n depend on the specific gravity. In this study, the specific gravity was determined following the ASTM D 854 standard (Bardet, 1997). The materials and equipment needed for specific gravity test were dry sand sample, distilled water, 250 mL volumetric flask, balance (accuracy 0.01 g), aluminum dish and oven.

Test procedure was conducted under the room temperature. Four dry sand samples were prepared to ensure a reliable result. The samples were placed in a dish and then spiked with distilled water to make a sand-water mixture. Four empty aluminum dishes and four empty flasks were weighed. The mixture was poured into the flask and agitated gently to remove the air. Distilled water was added carefully until the flask was filled. Next step was to measure the mass of the filled flask. After that, the flask was emptied and the sand-water mixture was poured into the aluminum dish. Samples were then dried in the oven for 24 hours.

Mass of dried sand then weighed and the specific gravity was calculated using Equation 26 as follows:

$$G_s = \frac{W_s}{W_s + W_{fw} - W_{fs}} \tag{26}$$

where G_s is the specific gravity, W_s the mass of dry sand, W_{fw} the mass of flask filled with distilled water only and W_{fs} the mass of flask filled with sand-water mixture. Characteristics each variable in the tests and the specific gravity are presented in Table 5.

Table 5. Specific gravity test on quartz sand

Description	Sample 1	Sample 2	Sample 3	Sample 4
Mass of flask (g)	100.32	94.14	98.06	88.85
Mass of aluminium dish (g)	5.96	5.98	5.55	5.56
Mass of flask and water(g)	349.75	343.53	347.38	338.10
Mass of flask, sand and water (g)	424.21	423.85	409.37	399.94
Mass of sand and aluminium dish (g)	125.74	136.05	105.36	105.46
Mass of dried sand (g)	119.78	130.07	99.81	99.90
Specific gravity G_s	2.64	2.61	2.64	2.62
Average specific gravity G_s		2.63		

4.2.2 Method of Filter Column Construction

Construction of filter columns in the pre-experiment phase and Phase I was using free falling method while in Phase II, water pluviation method was used. In the free falling method, the dry sand was poured gradually and carefully into an empty column with the help of a funnel. During the sand pouring, the funnel was rotated horizontally allowing the sand to be distributed evenly in the entire filter area. After the sand was loaded into the column up to the desired height, the water was introduced slowly in the up-flow direction to avoid short circuiting as seen in Figure 15. Another reason for the up-flow direction was to reduce the air bubbles that were trapped within the filter bed. In the free falling process, compaction of sand was only due to the gravitational force. One disadvantage of this method was the formation of fine grain layers because of the rapid settlement of coarser grains. At the top of the sand surface, there was also this fine grain layer. The existence of this layer might lead into faster clogging period because mostly removal in slow sand filtration occurs at the top of sand bed.

The difference between the water pluviation method and the free falling method laid only on the introduction of water. Prior to the sand loading, water was filled into the column carefully under the up-flow direction until certain height. The water level should not be too high to avoid the overflow due to the sand loading. After that, the process was the same as in the free falling method where the sand was gradually loaded to the filter. The loading was done carefully with a funnel to minimize the development of air bubbles when the sand entering the water layer. Settlement of sand was also because of gravity but the velocity is slower than from the free falling method due to the existence of water inside the column, however, similar disadvantage on the formation of fine grain layers was still found. An advantage of this method was that the sand grains were arranged inside the water medium therefore, the interspaces between grains were filled with water. As a consequence, the air bubble development could be reduced.

Figure 15. Short circuiting in the filter column

4.2.3 Selection of Surrogate Material and Turbidity Correlation

In order to maintain a constant quality of influent, artificial raw water created from a mixture of solid material and tap water was used. In this study, the turbidity is used as the controlled parameter to describe the quality of artificial raw water. For this purpose, the turbidity should change linearly as a function of suspended solid concentration. At the beginning, four materials i.e. natural soil (*Heilerde*), silica powder (*Millisil W12*), silica gel and rock powder were evaluated in order to select the most suitable surrogate material to represent suspended solids in the artificial raw water.

Prior to the creation of suspension, natural soil, silica powder, silica gel and rock powder were sieved using 63 µm sieve. Each type of solids was then mixed with tap water under varied concentration. Mixing process was done using a magnetic stirrer for 15 minutes as seen in Figure 16. After that, the suspension was decanted and the turbidity was measured using the Hach Lange 2100Q Portable Turbidimeter. Allowance for the turbidity measurement was set for ± 10%. In order to investigate the correlation between the turbidity and the suspended solids concentration, four different concentrations were tested (Table 6).

Figure 16. Artificial raw water created from a mixture of natural soil and tap water under varied concentration. The most transparent water has the lowest concentration of suspended solids and turbidity value.

Table 6. Turbidity correlation according to the type of suspended solids

Suspended solid concentration (mg/L)	Turbidity by natural soil (NTU)	Turbidity by silica powder (NTU)	Turbidity by silica gel (NTU)	Turbidity by rock powder (NTU)
50	4.16	21.40	1.61	23.06
250	32.09	121.33	2.45	104.64
500	67.00	252.00	3.50	222.86
1000	153.33	581.00	3.15	956.30

The values of measured turbidity are plotted in Figure 17. According to the regression analysis, relationship between suspended solids concentration and turbidity for natural soil and silica powder was strongly linear. However, the analysis for silica gel and rock powder showed that the relationship between suspended solids and turbidity was not linear. Concentration of silica gel in the liquid did not affect the turbidity values. Meanwhile for rock powder, exponential regression fit more properly than linear regression. Based on this result, silica gel and rock powder were omitted as potential surrogate material in the raw water.

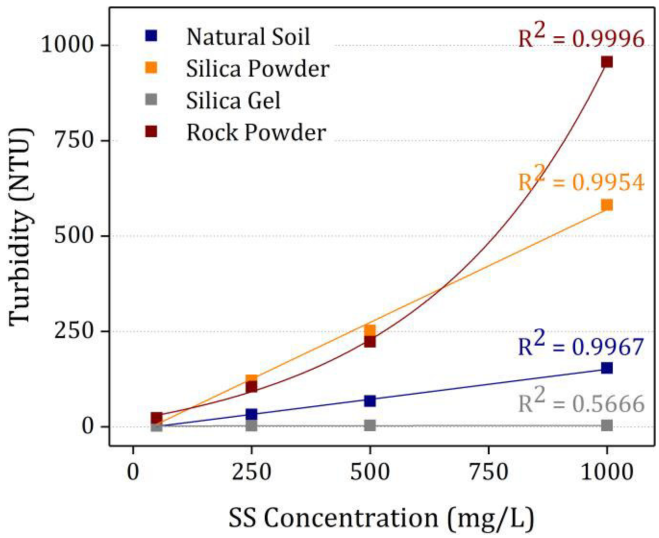


Figure 17. Relationship between turbidity and suspended solids concentration for natural soil, silica powder, silica gel and rock powder

At the beginning, natural soil was chosen as the surrogate material solely because the standard error of natural soil in the regression analysis was lower than the silica powder. However, after some tests in the pre-experiment phase and the test of influence of the d_{10} in Phase I, it was observed that the settling velocity of natural soil was quite fast. Then the settling velocity of the natural soil and the second potential surrogate material, silica powder, was compared. The approach was by determining the grain size distribution of both materials followed by the calculation of the settling velocity using Equation 25. Measurement of particle size was conducted using EyeTech Particle Size and Shape Analyzer.

Output from the particle size measurement indicated that silica powder has a larger fine fraction than the natural soil (see Figure 17). Larger content of fine fraction in the silica powder causes lower settling velocity of particle compared to the natural soil. Comparison of settling velocity for both materials based on the value of d_{10}, d_{50} and d_{90} is shown in Table 7. Based on the settling velocity of natural soil which was higher than the applied hydraulic loading rate (see Section 2.7.2), sedimentation was the only mechanism that worked for the complete removal (see Section 2.6). Therefore, for the rest of the tests in Phase I and Phase II, silica powder was used as surrogate material to create the artificial raw water.

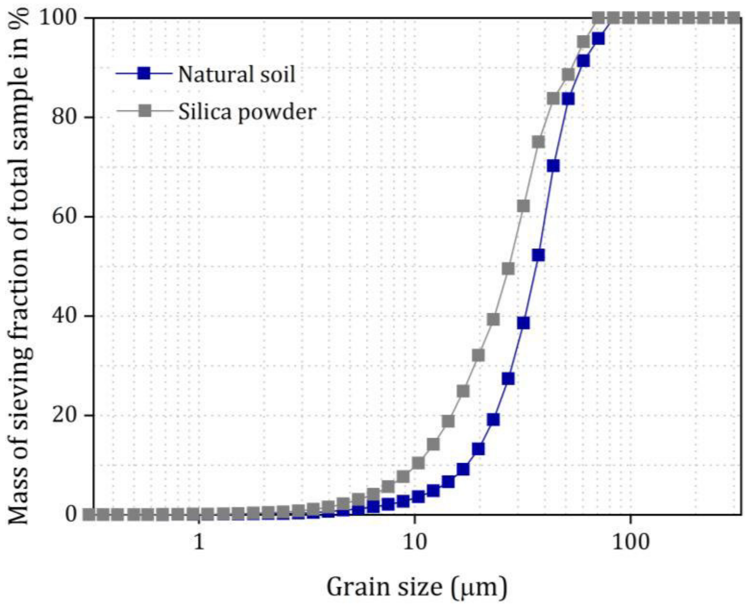


Figure 18. Grain size distribution of natural soil and silica powder

Table 7. Settling velocity (20 °C) of natural soil and silica powder according to d_{10}, d_{50} and d_{90} of particles

Parameter	Ø (µm)		Settling Velocity (m/h)	
	Natural soil	Silica powder	Natural soil	Silica powder
d_{10}	16.11	9.18	0.84	0.27
d_{50}	34.85	26.08	3.93	2.20
d_{90}	54.33	51.58	9.55	8.61

4.2.4 Selection of Suitable Supernatant Level

Focus on this test was to select the suitable supernatant level for the filter operation during the experimental phases. Influence of constant and decreasing supernatant levels on the slow sand filtration performance was investigated. The investigation was performed with distilled water as the inlet in order to minimize the effect of particle addition on the alteration of the hydraulic loading rates. For the test, four filter columns were constructed with the same grain size distribution of media, d_{10} of 0.26 mm and C_u of 2.5. All filter columns consisted of 30 mm supporting layer, 200 mm filter bed and 20 mm protection layer. Two columns were operated under constant head i.e. Constant-Filter 1 and Constant-Filter 2. The other two columns were operated under decreasing head i.e. Decreasing-Filter 1 and Decreasing-Filter 2.

Columns with constant head mode were operated with a constant *Δh* (Figure 19a). In order to maintain the constant supernatant level, the principal of communicating vessel was adopted. In the decreasing head mode, the supernatant level was allowed to drop from the maximum level to the minimum level (Figure 19b). Once the supernatant reached the minimum level, the operation was stopped and restarted after the supernatant was in the maximum level.

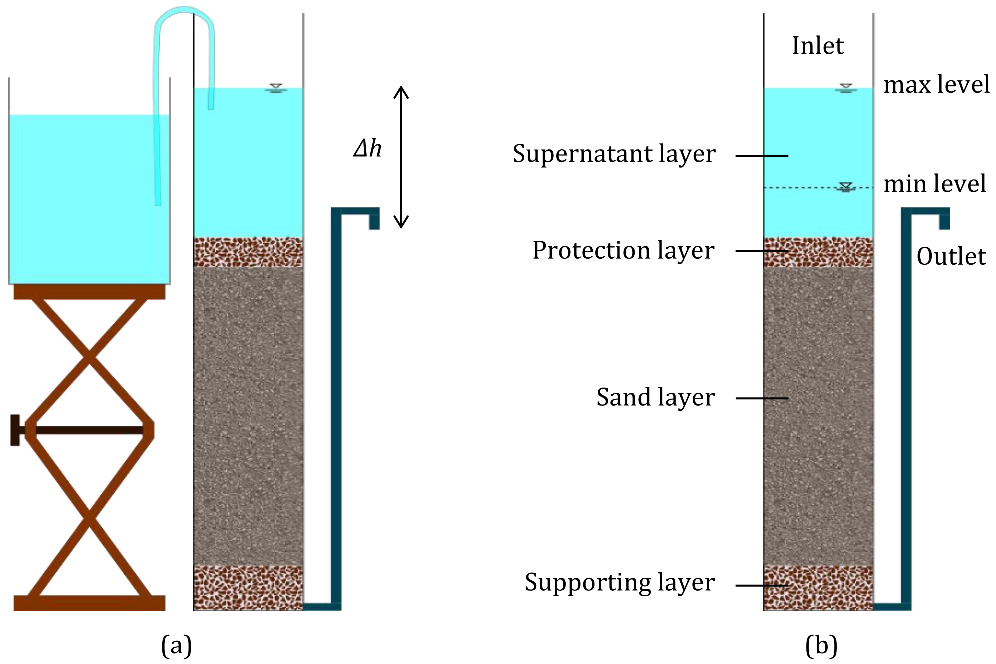


Figure 19. Scheme of filter columns operated under constant and decreasing head (*not drawn to scale*)

Evaluation on the filter behavior under constant and decreasing supernatant levels was based on the development of hydraulic loading rate. In the filter columns operated under constant supernatant layer, the trend of hydraulic loading rate was constant as illustrated in Figure 20. Meanwhile, in the decreasing mode, average hydraulic loading rates were likely to decline from the initial value. Considering that there was no addition of suspended solids to the filter bed which might lead into clogging, the behavior of filter columns with decreasing supernatant level was quite distinctive. According to the previous literatures, this decrease in hydraulic conductivity might be as a result of compaction in the filter bed during the operation which altered its capacity to transport water (Bardet, 1997; Hatt *et al.*, 2008). This changing of the capacity might occur not only due to the frequent openings and closings of the valve but also inconsistent hydraulic loading rate.

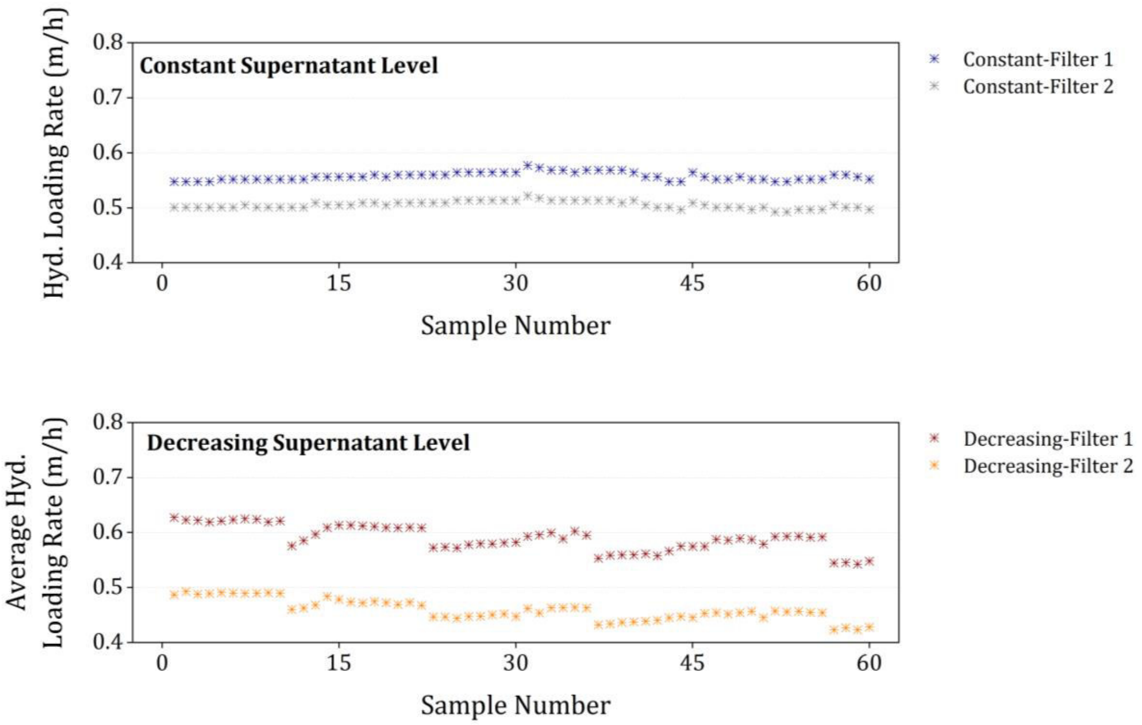


Figure 20. Development of hydraulic loading rate in the filter columns operated under constant and decreasing supernatant layer

Considering the behavior of hydraulic loading rate, constant supernatant level was chosen to be the most suitable operation mode for the experimental phases. It was expected by operating the filter columns under constant supernatant layer, no effect such in the decreasing mode might occur during the experiments. Another consideration was that the supernatant layer could act as a damper so that every time the artificial raw water was fed to the column, the sand bed surface was not disturbed. Maintaining the condition of sand bed surface is important due to the development of filter cake that occurs on the filter surface.

4.2.5 Setup of Filter Columns with Variation in d_{10}

Trial on the experimental setup for varied d_{10} was conducted by comparing fine and coarse grain size distributions of media. Fine and coarse media were represented by d_{10} of 0.075 mm and 0.50 mm respectively with the same C_u of 2.5. Values of d_{10} that were tested in this phase were not in the range of recommended values 0.15-0.35 mm (see Table 1). This condition was intended to investigate the performance of filter under the extreme media size. Each filter column consisted of three layers i.e. 50 mm supporting layer, 200 mm sand layer and 20 mm protection layer (see Figure 19). Gravel size used for supporting and protection layers was 2-6.3 mm. Outlet position was always above the protection layer to ensure that the sand layer was always potentially saturated.

After the filter columns were constructed, its characteristics related to the values of porosity, specific surface area and initial hydraulic conductivity was determined. In the whole tests of this study, the hydraulic conductivity measurement was always conducted with the constant head method. The main reason was because the flow of water through the filter media was too rapid to be measured with falling head test. In order to identify the clogging pattern, hydraulic conductivity measurements were carried out for at least two times i.e. initial one when the filter bed was still clean and final one when the filter has been loaded with solids which come from the raw water. The design of filter column did not allow the hydraulic conductivity measurement for the filter bed only because the water flowed through the whole layers including the protection and supporting layer. However, the hydraulic conductivity is significantly influenced by the finest grain within the system. Therefore, it was assumed that the presence of protection and supporting layer had an insignificant effect to the degree of hydraulic conductivity of filter column. Based on the value of initial hydraulic conductivity, the initial hydraulic loading rate could be set-up by adjusting the Δh. Initial hydraulic loading rate for both columns in this test was set at 0.18±0.05 m/h.

Artificial raw water was created by mixing the natural soil and tap water under the concentration of 1000 mg/L or 250±25 NTU. Intermittent mode was selected as the method of filter operation for the whole experimental phases. The basic reason was because with the intermittent mode, the amount of water filtered and the mass of solids could be controlled easier which was very important for conducting the systematic investigation. During the filter operation, a volume of 300 mL was fed to the column for each filter run. Performance of filer columns was evaluated based not only on the comparison of inlet and outlet water turbidity but also on the filter behavior in regard to the development of hydraulic conductivity and head loss. In order to observe the clogging potential, hydraulic conductivity was measured after every three feedings. For the head loss, the values of each column would be comparable by converting them into normalized head loss at certain hydraulic loading rate. In this study, the normalized head loss was calculated using the formula from Sugimoto (2014) at the hydraulic loading rate of 0.20 m/h (see Equation 27).

$$Head\ loss\ normalization\ (cm) = \frac{Head\ loss\ (cm)}{Flow\ rate\ \left(\frac{m}{h}\right)} \times Normalized\ flow\ rate\ \left(\frac{m}{h}\right) \tag{27}$$

4.2.6 Setup of Filter Columns with Variation in C_u

Experimental setup for varied C_u was also conducted in this pre-experiment phase. Two filter columns i.e. C_u 2.5 and C_u 5 were constructed for this test. Both filter columns had the same d_{10} of 0.15 mm. Configuration of filter columns was as follows: 30 mm of supporting layer; 250 mm of sand layer; and 20 mm of protection layer. Initial hydraulic conductivity test was conducted to set-up the hydraulic loading rate of 0.2±0.05 m/h. Natural soil was used as a surrogate material to create the artificial raw water with a concentration of 1000 mg/L with turbidity of 250±25 NTU. The feeding rate for each filter column was 500 mL/day. Evaluation of filter performance was based on the turbidity removal and development of relative hydraulic conductivity and normalized head loss at 0.20 m/h. The calculation of the relative hydraulic conductivity Δk was done by adopting the method of Schwarz (2004) as follow:

$$\Delta k = \frac{k_{(m)}}{k_{(0)}} \tag{28}$$

where $k_{(m)}$ is the hydraulic conductivity at solids mass m (m/s) and $k_{(0)}$ is the initial hydraulic conductivity (m/s).

4.2.7 Influence of Protection Layer on Suspended Solids Removal

The influence of the protection layer on the filter performance on turbidity removal was studied by constructing two filter columns i.e. WOPL[1]-Filter and WPL[2]-Filter. Filter media that was used for this test was directly taken from the package provided by the supplier without any modification. The grain size distribution of the sand was represented by d_{10} of 0.20 mm and C_u of 1.74. Both filter columns consisted of 30 mm supporting layer and 300 mm sand layer. One filter was added with 20 mm protection layer.

Initial hydraulic conductivity was determined after the filter column construction and a hydraulic loading rate of 0.6±0.15 m/h was set. Silica powder was used as the surrogate material to create the artificial raw water (220 mg/L and 100±10 NTU). In every feeding, 2000 mL of artificial raw water was filtered. At the end of filter operation, final hydraulic conductivity was also measured so that the effect of solids addition to the filter capacity could be observed. The outlet turbidity from both filter columns was also evaluated by conducting One Way Analysis of Varian (ANOVA) test to find out whether the performance of both filter was equal. The ANOVA test basically uses the variance of the sample means to indicate whether they are difference or not (Schumacker and Tomek, 2013). The sample means are homogeneous if they are similar. On the other hand, if the differences are quite large then the sample means are heterogeneous. In this study the ANOA test was performed by using the data analysis from Microsoft Excel. At the end of the calculation, the results will show the *p-value*. This *p-value* will be compared with the significance factor α. If the *p-value* is higher than the α then it can be concluded that the sample means are not significantly different.

[1] WOPL = without protection layer

[2] WPL = with protection layer

4.3 Phase I

4.3.1 Large Scale Filter Columns with Variation in d_{10}

The experimental setup of this first test in Phase I consisted of two similar sets, i.e. Set 1 and Set 2, of filter columns. Set 1 consisted of five filter columns with five different grain size distributions which varied in d_{10} i.e. d_{10} 0.075 mm, d_{10} 0.15 mm, d_{10} 0.26 mm, d_{10} 0.40 mm and d_{10} 0.50 mm (see Figure 21). Set 2 consisted of four filter columns with the same grain size distributions as in Set 1 but without the d_{10} 0.075 mm. Three values of d_{10} represented the recommended values (see Table 1) while d_{10} of 0.075 mm and 0.50 mm represented the extreme fine and coarse media respectively. The heterogeneity of sand fraction was represented by C_u of 2.5.

Figure 21. Phase I - Construction of filter columns in Set 1

The principal procedures tested in Section 4.2.5 such as the operation mode, sampling and methods of parameters measurement were adopted for this investigation. Operating variables such as bed depth and hydraulic loading rate of both sets were maintained equal. Configuration of each filter column consisted of 100 mm stratified gravel as supporting layer (see Section 4.2.1), 500 mm sand layer and 200 mm protection layer (see Figure 22). The characteristic of each filter column was identified from the values of void ratio and porosity, specific surface area and hydraulic conductivity. The hydraulic loading rate was set at 0.20±0.05 m/h.

Filter columns were fed up with artificial raw water created from a mixture of natural soil and tap water. Concentration of the artificial raw water was 380 mg/L and the turbidity was 100±10 NTU. In every filter run, a volume of 3000 mL was fed to the column. Both sets of filter columns were under operation for 6 weeks. At the beginning of each week, 7000 mL of artificial raw water were added to the column in order to create the supernatant layer (Δh). At the end of the week, the hydraulic conductivity was measured to observe its development. After the measurement of hydraulic conductivity, the water was allowed to drop until 2 cm above the protection layer to ensure that the sand bed was potentially saturated. Filtrate samples were taken two times per filter run followed by the measurement of turbidity and particle size. One Way ANOVA test was carried out to evaluate the difference of outlet turbidity from each filter column. Another parameter used to evaluate the filter performance was the development of relative hydraulic conductivity and normalized head loss at 0.2 m/h.

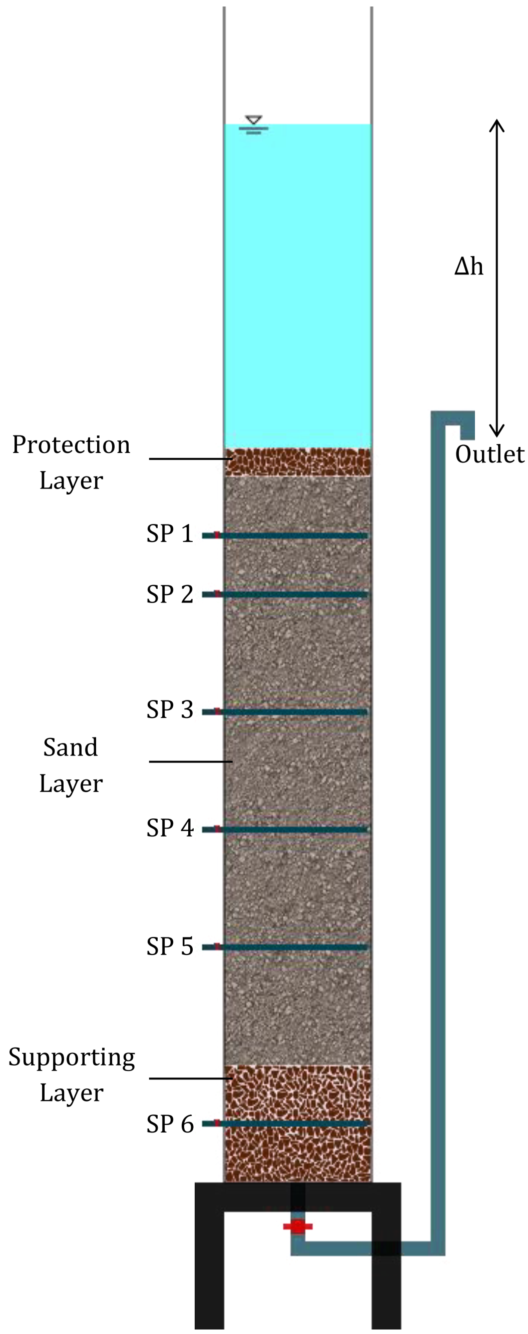


Figure 22. Phase I - Sketch of large filter column (*not drawn to scale*)

4.3.2 Large Scale Filter Columns with Variation in C_u

Three similar sets of filter columns i.e. Set A, Set B and Set C, were constructed for this investigation. Every set consisted of three filter columns with different grain size distribution which varied in the C_u. The filter columns with narrow grain size distribution were represented by C_u 2.5 and C_u 3 while the filter column with wide grain size distribution was represented by C_u 5. The C_u of 2.5 and 3 were tested to validate the recommended values (see Table 1) while the C_u of 5 was used to investigate how a wide grain size distribution affects the filter performance. Other operating variables such as d_{10} (0.26 mm), bed depth, operation mode and hydraulic loading rate were controlled to be equal for all filter columns. Configuration of the filter columns was exactly the same to the previous experiment on d_{10} (see Section 4.3.1, Figure 22). After the filter column construction, physical properties of filter represented by void ratio, porosity and hydraulic conductivity were determined. Hydraulic loading rate was set up at 0.2±0.02 m/h for each filter column.

Artificial raw water in this test was created by mixing tap water and silica powder. Concentration of suspended solids in the inlet was 220 mg/L and the turbidity was 100±10 NTU. At the beginning of every week, head drop for each column was created using 2500 mL of artificial raw water. Then, for the next five days each filter column was fed with a volume of 2500 mL every day. All filter columns were operated intermittently with constant supernatant layer during seven weeks. Measurement of hydraulic conductivity was conducted by the end of every week. After the hydraulic conductivity measurement, the supernatant layer was allowed to drop until zero pressure.

Assessment of the slow sand filtration performance was based on some parameters such as, turbidity, TSS and particle size. Determination of TSS was done by the gravimetric method as described in Section 2.1. As the focus of this research experiment was to find out the influence of C_u on the slow sand filtration performance, the capability of each filter on removing the turbidity and TSS was compared and analyzed using the ANOVA test. The statistical analyses were conducted at 95% level of confidence ($\alpha = 0.05$). Development of relative hydraulic conductivity and normalized head loss at 0.20 m/h were also observed during the study.

4.3.3 Large Scale Filter Columns with Variation in C_u Operated Under High Hydraulic Loading Rate

In this test, three sets of filter columns i.e. Set A, Set B and Set C from the previous test on varied C_u were used. Hence, the grain size distribution of filter media was the same but the initial hydraulic conductivity was different from the previous test. It is because certain mass of solids was already deposited in the filter bed and affecting the filter capacity. The test was conducted for eight weeks long. The filter columns were operated using the same procedure as in the previous test described in Section 4.3.2 except the total volume of artificial raw water loaded to create the supernatant layer at the beginning of each week and the hydraulic loading rate (0.6±0.15 m/h). Parameters measured during the test were turbidity, TSS and particle size. Development of turbidity at the outlet, relative hydraulic conductivity and head loss was also evaluated. Gradual change in the relative hydraulic conductivity during the filter run under 0.2±0.05 m/h and 0.6±0.15 m/h is also presented in the result.

4.4 Phase II

4.4.1 Small Scale Filter Columns with Variation d_{10}

The systematic investigation on the influence of d_{10} was conducted using five filter columns varied in d_{10} i.e. d_{10} 0.075 mm, d_{10} 0.26 mm, d_{10} 0.50 mm, d_{10} 0.70 mm and d_{10} 0.90 mm. Those five different grain size distributions had the same C_u of 2.5. The first three d_{10} values were adopted from the large-scale test (see Section 4.3.1) and the two other values were used to study the influence of the extreme condition on the filter performance. Filter columns were constructed without protection layer as illustrated in Figure 23. Filter construction was done using the water pluviation method.

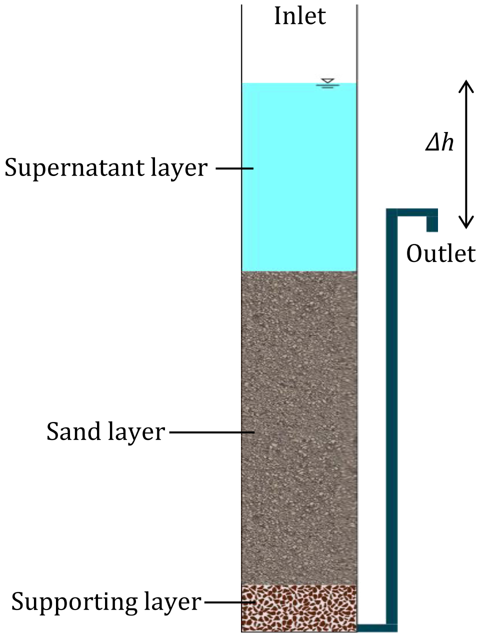


Figure 23. Phase II - Sketch of small filter column without protection layer (*not drawn to scale*)

Physical characteristic of columns such as the void ratio and porosity, hydraulic conductivity, and specific surface area was determined after the construction. After the initial hydraulic conductivity was measured, an initial hydraulic loading rate of 0.45±0.10 m/h was established. During the filter operation, the height of supernatant layer and outlet position was maintained constant. Consequently, hydraulic loading rate decreased by the deposition of solids in the sand bed. By allowing the hydraulic loading rate to decrease, clogging pattern of every column can be observed. Feeding of columns was done at the rate of 1000 mL/day. The artificial raw water was created from tap water and silica powder (45±5 NTU, 110 mg/L). The experiments were performed for seven weeks.

Slow sand filtration performance was evaluated by analyzing several parameters i.e. turbidity, TSS, particle size distribution of the outlet and development of relative hydraulic conductivity and normalized head loss at 0.20 m/h.

In this test, after the turbidity value was determined, the sample in the cuvette was poured back to the diluted sample in the Erlenmeyer flask. This sample was then dried for 24 hours in the oven. The dry sample was weighed and sieved with a sieve opening of 0.063 mm. Mass of sand sample >0.063 mm was measured. The portion of fine fraction <0.063 mm was calculated based on the percentage of sand composition in Table 4. Mass of retained suspended solids was estimated by subtracting the total mass of sand sample to the mass of sand fraction. According to this analysis, the percent surface removal by filter cake formation and straining could be calculated.

4.4.2 Small Scale Filter Columns with Variation in C_u

In the investigation of the influence of C_u on the removal and penetration of solids, three filter columns varied in C_u, i.e. C_u 2.5, C_u 3 and C_u 7 were constructed. The d_{10} of all columns was the same that is 0.26 mm. Two C_u values, 2.5 and 3, were taken from the large scale test (see Section 4.3.2) while the C_u of 7 was used to investigate the extreme condition. The same configuration of filter columns as in the previous test in Section 4.4.1 was employed (see Figure 23). In this test, the filters were operated for seven weeks with constant height of supernatant layer but the outlet position of every column was always adjusted to maintain the same hydraulic loading rate of 0.20±0.05 m/h during the experiment. Filter columns were fed intermittently using artificial raw water created from silica powder and tap water (220 mg/L, 100±10 NTU) at the rate of 1000 mL/day. Performance of filter columns was then evaluated after several parameters i.e. turbidity, TSS, development of relative hydraulic conductivity and normalized head loss at 0.20 m/h, particle size distribution and solids penetration.

4.4.3 Small Scale Filter Columns with Variation in Hydraulic Loading Rates

In order to investigate the influence of hydraulic loading rate on the solids removal and penetration, three filter columns with similar d_{10} of 0.26 mm and C_u of 2.5 were constructed. Each filter column was operated under different hydraulic loading rate i.e. 0.08±0.02 m/h, 0.20±0.05 m/h and 0.8±0.2 m/h. Similar to the two previous tests (see Section 4.4.1 and 4.4.2), filter columns in this test were without the protection layer (see Figure 23). Each filter column was characterized by its void ratio and porosity, specific surface area and initial hydraulic loading rate. The procedure of filter operation in this test was adopted from the previous test described in Section 4.4.2. Therefore, the quality of artificial raw water (220 mg/L, 100±10 NTU), rate of feeding (1000 mL/day), duration of experiment and operation mode were similar to the small scale test of varied C_u. Evaluation of filter performance was also based on the turbidity and TSS removal, development of relative hydraulic conductivity and normalized head loss at 0.20 m/h and the solids penetration in the sand bed.

4.4.4 Evaluation on the Use of Protection Layer to Prolong Filter Run Time

In 2006, Mälzer and Gimbel had done a study in regard to the effect of protection layer to increase the filter run time. A similar experiment was conducted in this study by employing gravel as protection layer. The study was completed with the analysis on the solids penetration. The objective was to identify how the solids penetrated in the protection layer, so that the role of gravel as protection layer to increase the filter run time could be validated. In order to accommodate this objective, a new filter column with d_{10} of 0.26 mm and C_u of 2.5 was constructed with the configuration as follows: 30 mm supporting layer, 200 mm sand layer and 20 mm protection layer. The approach in this test was to compare the performance of this new constructed filter column and filter column with d_{10} 0.26 mm and C_u 2.5 from the previous test, which was constructed without protection layer (see Section 4.4.1). Each filter column was operated under the constant supernatant level with the adjustment of the outlet position to control the hydraulic loading rate at 0.20±0.05 m/h. The filter columns were operated intermittently and fed with artificial raw water (220 mg/L, 100±10 NTU) at the rate of 1000 mL/day for seven weeks. The performance of slow sand filtration was evaluated based on the turbidity and TSS removal, particle size distribution, development of relative hydraulic conductivity and normalized head loss at 0.20 m/h and the solids penetration.

5 Results and Interpretation

5.1 Filter Performance in the Pre-Experiment Phase

5.1.1 Comparison of Fine and Coarse Media

Characteristic of filter columns with d_{10} 0.075 mm and d_{10} 0.50 mm that were tested in the pre-experiment phase is presented in Table 8. From the values of initial hydraulic conductivity, it can be inferred that the water flowed easier in the filter column with coarse media. Equal hydraulic loading rate and the different values of initial hydraulic conductivity led to the variation in the initial head differences (Δh). For the turbidity removal, filter d_{10} 0.075 mm and filter d_{10} 0.50 mm achieved high efficiencies, i.e. 99.91 % and 99.89 % respectively, independently from the d_{10}. According to the outlet quality, filter d_{10} 0.075 mm and filter d_{10} 0.50 mm were able to reduce the turbidity from 250±25 NTU to below 1 NTU as presented in Figure 24. The values that can be read from the boxplot are the following:

a. 1st percentile value shown by the lower horizontal line of the whisker,

b. 25th percentile value shown by the bottom part of the box,

c. mean value shown by the little box,

d. median value shown by the horizontal line in the box,

e. 75th percentile value shown by the upper part of the box,

f. 99th percentile value shown by the upper horizontal line of the whisker, and

g. outlier value shown by the small cross.

Table 8. Pre-Experiment Phase - Characteristics of filter columns with fine and coarse media

Parameters	d_{10} 0.075 mm	d_{10} 0.50 mm
Initial Hydraulic Conductivity $k_{(0)}$ (m/s)	2.96×10^{-5}	4.90×10^{-4}
Initial Hydraulic Loading Rate (m/h)	0.17	0.16
Initial Δh (cm)	29	1.5

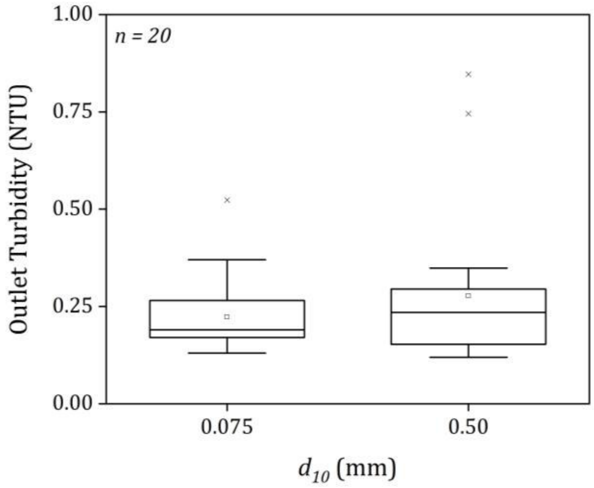


Figure 24. Pre-Experiment Phase - Outlet turbidity of filter d_{10} 0.075 mm and filter d_{10} 0.50 mm

Development of hydraulic conductivity and normalized head loss demonstrated the effect of suspended solids load to the filter behavior. Figure 25 shows a slight decrease of hydraulic conductivity in filter d_{10} 0.075 mm and filter d_{10} 0.50 mm. Initial hydraulic conductivity for filter d_{10} 0.075 mm and filter d_{10} 0.50 mm decreased only for 7 % and 2 % respectively at the end of filter operation. A very low decrease indicated that an addition of 6300 mg solids in the filter bed was insignificant for the hydraulic conductivity of both filter columns. However, a presumptive basis that filter d_{10} 0.075 mm would experience faster clogging period could be made by considering two reasons i.e. the lower initial hydraulic conductivity and the decrease of hydraulic conductivity after 6300 mg solids load which was around three times higher than filter d_{10} 0.50 mm.

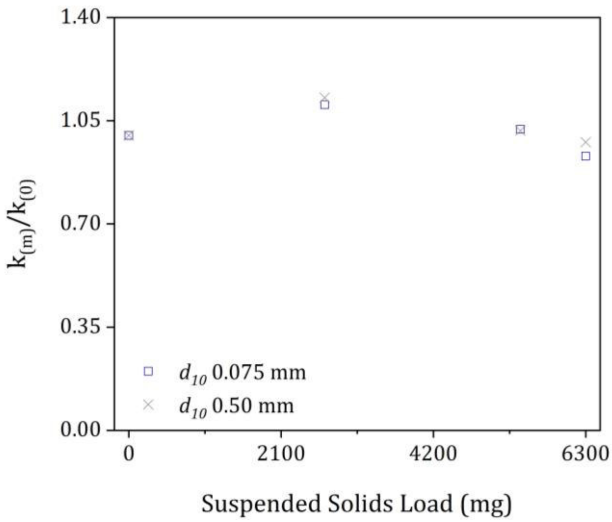


Figure 25. Pre-Experiment Phase - Development of relative hydraulic conductivity in filter d_{10} 0.075 mm and filter d_{10} 0.50 mm

The decrease of hydraulic conductivity caused an increase in the head loss. In Figure 26, the gradual increase of normalized head loss at 0.20 m/h due to the suspended solids load was plotted. According to the graph, it could be inferred that the head loss was significantly affected by the solids that retained in the filter bed. In regard to the clogging pattern, interpreting the gradual increase of normalized head loss at 0.20 m/h during the filter operation could be a promising approach. According to the findings either on the decrease of hydraulic conductivity or increase of normalized head loss, the degree was always greater for filter d_{10} 0.075 mm rather than filter d_{10} 0.50 mm.

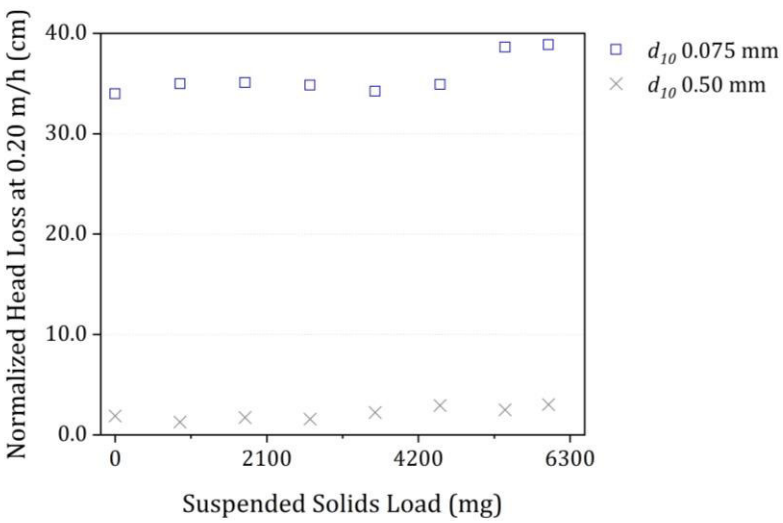


Figure 26. Pre-Experiment Phase - Development of normalized head loss at 0.20 m/h in filter d_{10} 0.075 mm and filter d_{10} 0.50 mm

5.1.2 Comparison of Narrow and Wide Graded Media

Trial on the experimental setup for filter columns with varied C_u was done by constructing two filter columns which had the characteristics presented in Table 9. Both filter C_u 2.5 and filter C_u 5 performed well in reducing the turbidity from 250±25 NTU to below 2 NTU (Figure 27). Filter C_u 2.5 reached averagely a slightly higher turbidity removal (99.64 %) than filter C_u 5 (99.47 %). This result was contradictory from previous studies by Di Bernardo and Escobar Rivera (1996) and Zipf *et al.* (2016) (see Section 2.7.1). However, it is worth noting again that in the study of Zipf *et al.*, the filter with highest C_u had the smallest d_{10}. Consequently, it was difficult to evaluate whether the higher removal turbidity was caused by the higher C_u or lower d_{10}. The approach in this study was more promising because the d_{10} was the same for all filter columns therefore the influence of various C_u could be investigated independently.

Table 9. Pre-Experiment Phase - Characteristics of filter columns with varied C_u

Parameters	C_u 2.5	C_u 5
Initial Hydraulic Conductivity $k_{(0)}$ (m/s)	2.61×10^{-4}	1.39×10^{-4}
Initial Hydraulic Loading Rate (m/h)	0.23	0.21
Initial Δh (cm)	6.5	12

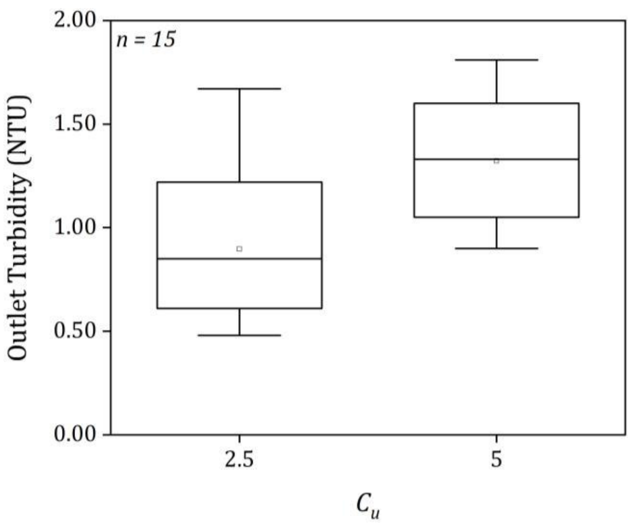


Figure 27. Pre-Experiment Phase - Outlet turbidity of filter C_u 2.5 and filter C_u 5

Filter column with narrow graded media had a higher value of initial hydraulic conductivity. However, at the end of filter operation, the hydraulic conductivity of filter C_u 2.5 was lower than filter C_u 5. After 8000 mg solids load, the initial hydraulic conductivity of filter C_u 2.5 decreased up to 67 % while for filter C_u 5 was only 25 %. Figure 28 shows that the solids load affected the changes of hydraulic conductivity significantly. The relative hydraulic conductivity in filter C_u 2.5 was significantly greater than in filter C_u 5.

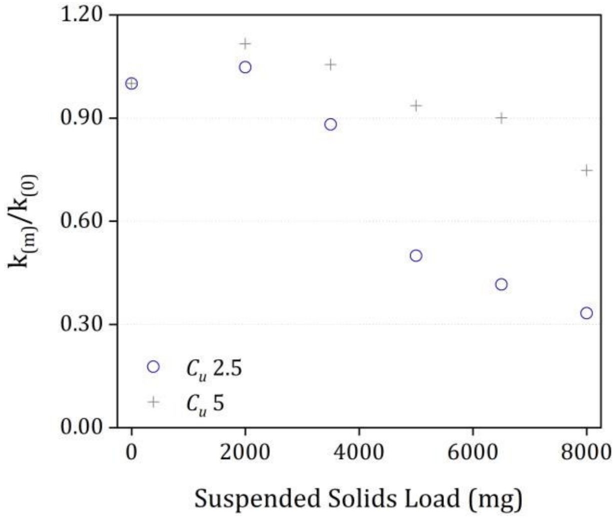


Figure 28. Pre-Experiment Phase - Development of relative hydraulic conductivity in filter C_u 2.5 and filter C_u 5

As a consequence of the decrease of hydraulic conductivity, the head loss was increased. Figure 29 shows that the normalized head loss at 0.20 m/h for filter C_u 2.5 increased from around 6 cm to nearly 30 cm. Meanwhile, in the filter C_u 5, the head loss increased from around 11 cm to nearly 20 cm. The discrepancies of the increase of head loss strengthened the proof that the filter with narrow graded media tended to clog faster than the wide graded media.

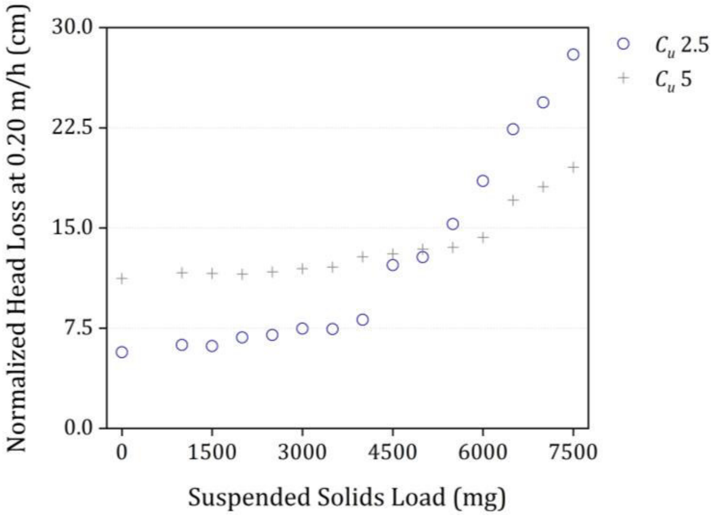


Figure 29. Pre-Experiment Phase - Development of normalized head loss at 0.20 m/h in filter C_u 2.5 and filter C_u 5

5.1.3 Effect of Protection Layer on Turbidity Removal

One of methods to maintain the sand bed surface undisturbed is by adding protection layer at the surface of filter bed which may serve as a damper for the water flow. However, the original design of slow sand filter does not have a protection layer. In this phase, an experiment in regard to the effect of protection layer, which was constructed from gravel (2–6.3 mm), on the turbidity removal was conducted. The characteristics of WOPL-Filter and WPL-Filter which were tested are listed in Table 10. Based on the measurement, the initial hydraulic conductivity of WOPL-Filter was slightly higher than WPL-Filter. It was because the protection layer also restricted the water flow through the porous media.

Table 10. Pre-Experiment Phase - Characteristics of filter column with and without protection layer

Parameters	WOPL-Filter	WPL-Filter
Initial Hydraulic Conductivity $k_{(0)}$ (m/s)	5.40×10^{-4}	4.63×10^{-4}
Initial Hydraulic Loading Rate (m/h)	0.60	0.60

Both filter columns achieved high percentage of turbidity removal i.e. 99.72 % for WOPL-Filter and 99.70 % for WPL-Filter (Figure 30). Outlet turbidity for both columns was reduced from 100±10 NTU to below 0.5 NTU independently from the protection layer. According to the ANOVA test (α 0.05), outlet turbidity from both filter columns was not significantly different with the p-value of 0.39511. Since the influence of protection layer on filter performance was deemed to be insignificant, all filter columns in Phase I was constructed with protection layer.

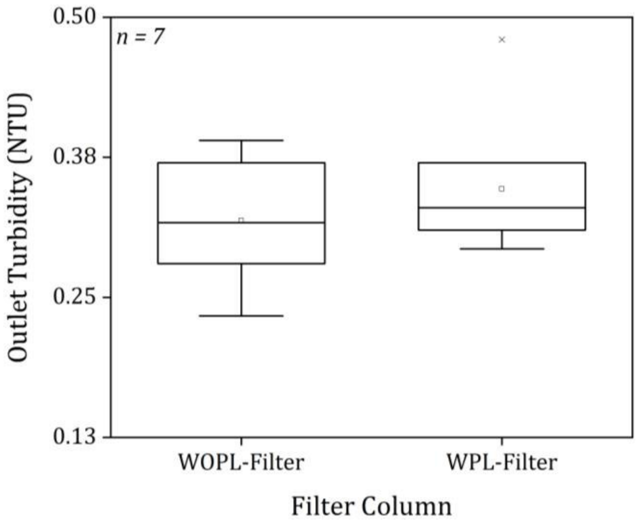


Figure 30. Pre-Experiment Phase - Outlet turbidity of WOPL-Filter (without protection layer) and WPL-Filter (with protection layer)

In Phase II, filter columns were constructed mostly without protection layer. It is because the focus of Phase II was to identify the removal mechanism by analyzing the solids penetration and the presence of protection layer may affect the solids deposition in the surface of filter bed.

5.2 Influence of the Grain Size Distribution on Suspended Solids Removal

5.2.1 Variation in d_{10}

The objective of this experiment was to evaluate the influence of varied d_{10} on the suspended solids removal. Characteristics of filter columns in Set 1 and Set 2 are summarized in Table 11. During the filter construction, the compaction of filter media was only by gravity. Therefore, the mass of sand which was loaded into the filter column was varied although the bed depth was equal for all filter columns. As a result, porosity values of filter columns were not similar one another.

Table 11. Phase I - Characteristics of filter columns in the test of varied d_{10}

Parameters	d_{10} 0.075 mm	d_{10} 0.15 mm	d_{10} 0.26 mm	d_{10} 0.40 mm	d_{10} 0.50 mm
Initial Hyd. Cond. $k_{(0)}$ (m/s)					
Set 1	9.25×10^{-5}	2.61×10^{-4}	4.36×10^{-4}	4.98×10^{-4}	8.27×10^{-4}
Set 2		6.76×10^{-5}	1.64×10^{-4}	4.72×10^{-4}	4.93×10^{-4}
Initial Hyd. Load. Rate (m/h)					
Set 1	0.20	0.19	0.18	0.19	0.20
Set 2		0.18	0.21	0.19	0.19
Initial Δh (cm)					
Set 1	40	14	11.5	9	5
Set 2		40	18	9.5	7.5

Values of initial hydraulic conductivity of filter columns in Set 1 and Set 2 were greatly influenced by the fine fraction. As expected, hydraulic conductivity of filter column with d_{10} of 0.075 mm was the lowest among others because it had a high content of fine fraction. On the contrary, in the filter columns with d_{10} of 0.50 mm, the content of fine fraction was the lowest among others. As a result, the values of initial hydraulic conductivity of both filter columns Coarse-2 were the highest in both sets. Effect of uncontrollable arrangement of voids and grains on the initial hydraulic conductivity could be observed clearly in this phase. From all of the filter columns that were constructed with the same grain size distribution, the same values of initial hydraulic conductivity were never being observed. This fact proved that it was impractical to construct identical filter columns even though both columns were constructed using the same filter media.

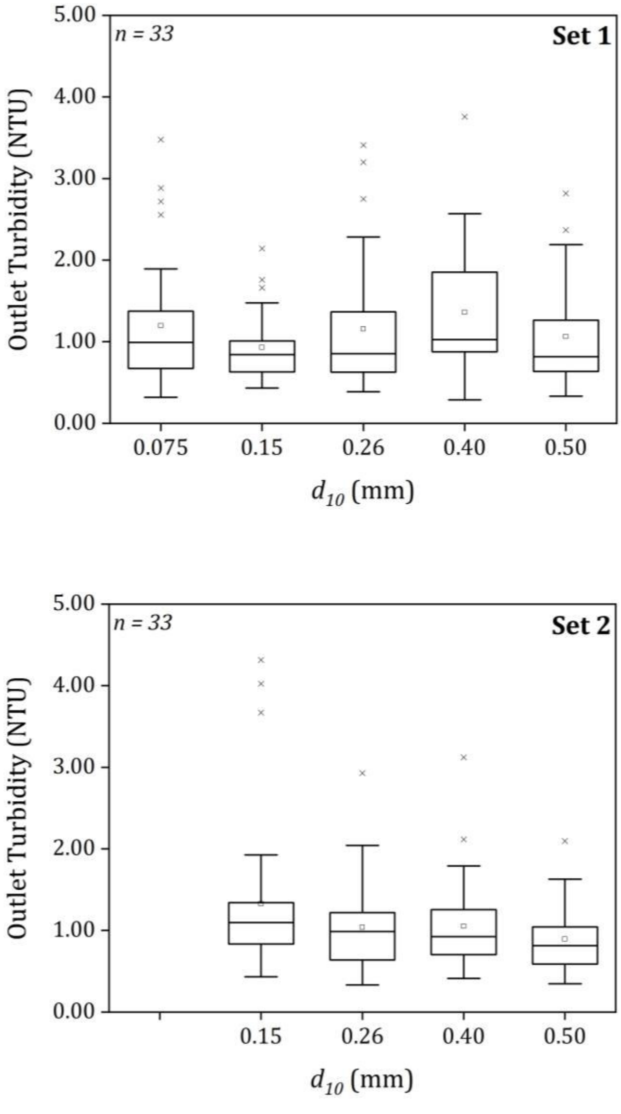


Figure 31. Phase I - Outlet turbidity of filter columns in the test of varied d_{10}

After six weeks of intermittent operation, both sets performed satisfactorily by reducing the inlet turbidity of 100±10 NTU to an average outlet turbidity of below 2 NTU independently from the d_{10} (see Figure 31). Both Set 1 and Set 2 could achieve an average turbidity removal of above 98.90 % (see Table 12). In order to identify the variation among the outlet quality of filter columns in both sets, the One Way ANOVA was performed. According to the results of the analysis, the p-values from both sets were higher than the significance level (α = 0.05) (see Table 13). These values represented that the population means of outlet turbidity of the filter columns in Set 1 and Set 2 were not significantly different.

Table 12. Phase I - Average turbidity removal of filter columns in the test of varied d_{10}

Set	Turbidity Removal				
	d_{10} 0.075 mm	d_{10} 0.15 mm	d_{10} 0.26 mm	d_{10} 0.40 mm	d_{10} 0.50 mm
Set 1	99.87 %	99.13 %	98.92 %	98.74 %	99.00 %
Set 2	-	98.74 %	99.03 %	99.02 %	99.15 %

Table 13. Phase I - Results of One Way ANOVA test at significance level of 0.05 in the test of varied d_{10}

Set	p-value
Set 1	0.1343
Set 2	0.0649

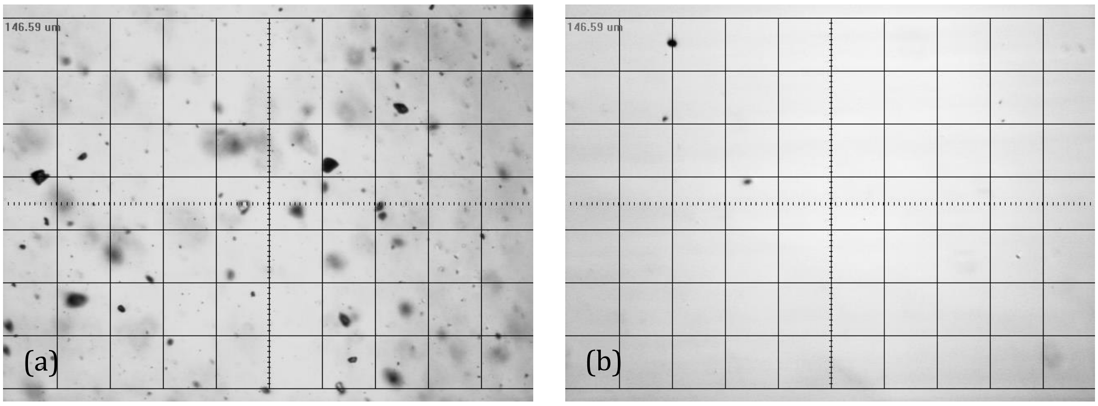


Figure 32. Phase I - Visualization of water quality in the inlet (a) and outlet (b) that was captured during the particle size distribution measurement

From the measurement of the particle size distribution of the outlet, size of the solids in terms of d_{10}, d_{50} and d_{90} could be obtained. How suspended solids removed after the filtration could also be observed by comparing the inlet and outlet visualization during the measurement (Figure 32). Considering the particle size distribution in the outlet, the filter column that was able to retain smaller size of solids could be determined. As presented in Figure 33, filter columns with finer media represented by d_{10} of 0.075 mm and 0.15 mm performed better on restraining smaller solids compared to other filter columns. Three other columns could wash bigger size of solids out. In these filter columns, it would be easier for the smaller size of solids to pass through the filter bed. However, those values are still higher than the size of bacteria and viruses that might exist in raw water. In this experiment bacteria and viruses were not taken into account.

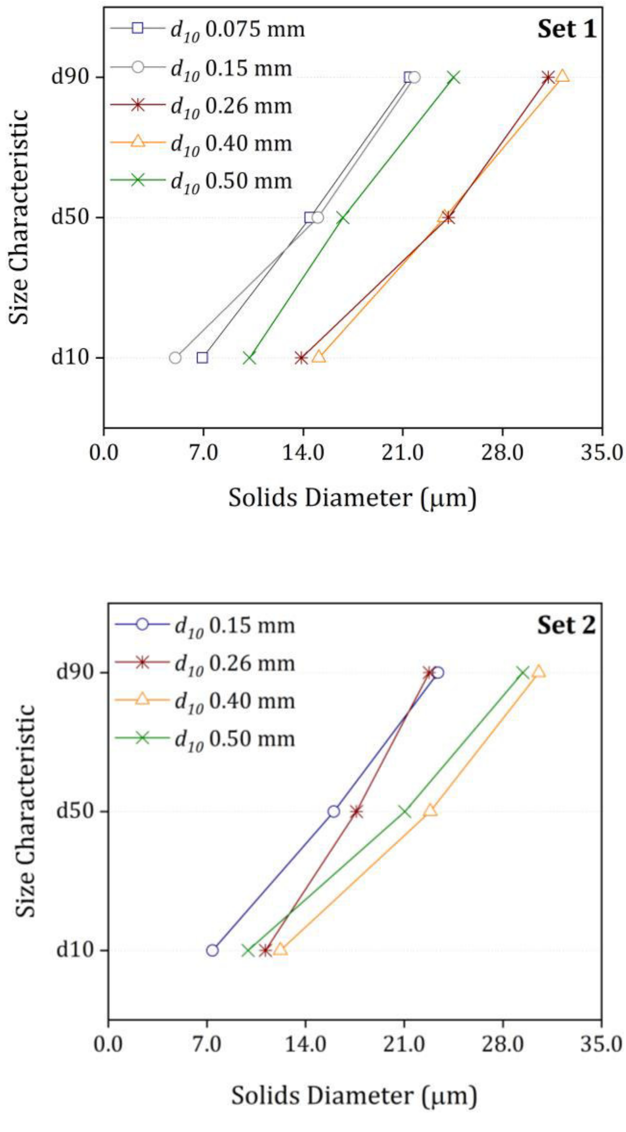


Figure 33. Phase I - Comparison of size distribution of solids in the outlet of filter columns in the test of varied d_{10}

The development of relative hydraulic conductivity (see Figure 34) and normalized head loss at 0.20 m/h (see Figure 35) was evaluated by taking Set 1 as a representative. Initial hydraulic conductivity of filter columns d_{10} 0.075 mm, d_{10} 0.15 mm, d_{10} 0.26 mm, d_{10} 0.40

mm and d_{10} 0.50 mm decreased up to 11 %, 13 %, 1 %, 30 % and 22 % respectively at the end of filter run. These percentages also showed that all filter columns were still in a good operation condition related to the problem of clogging. By referring to these percentages, filter d_{10} 0.075 mm and filter d_{10} 0.26 mm were likely to have more or less similar behavior toward the addition of solids in filter bed. The same tendency occurred in the filter columns with coarser media i.e. filter d_{10} 0.40 mm and filter d_{10} 0.50 mm. With only 1 % decrease, it indicates that the solids retained in filter bed did not influence the hydraulic conductivity of filter column d_{10} 0.26 mm yet. From the relative hydraulic conductivity shown in Figure 34, it indicated that the addition of 35,000 mg solids lowered the performance, in regard to the clogging, for less than 30 % for all filter columns.

According to the graph, the hydraulic conductivity decreases in filter columns d_{10} 0.075 mm, d_{10} 0.15 mm and d_{10} 0.40 mm were predominantly influenced by the solids load. On the contrary, the effect of solids load on the gradual changes in filter columns Fine-3 and Coarse-2 were found out to be minor. Even though the final hydraulic conductivity declined up to 22 % in filter d_{10} 0.50 mm, the development of gradual decrease was not as intense as others. Since filter d_{10} 0.075 mm had the lowest initial hydraulic conductivity and it decreased along with the suspended solid loads, it was predicted to experience the fastest clogging period.

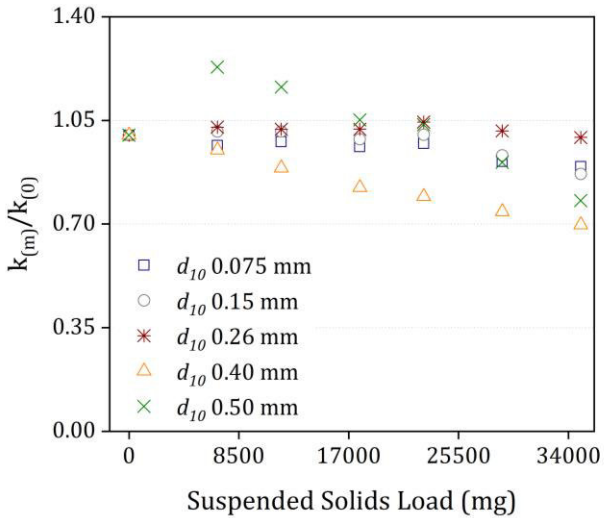


Figure 34. Phase I - Development of relative hydraulic conductivity of Set 1 in the test of varied d_{10}

Relationship between the addition of solids to the filter bed and normalized head loss at 0.20 m/h is represented in Figure 35. From the beginning of the filter operation, the head loss of all filter columns was varied as a consequence of different initial hydraulic conductivity values. With the addition of solids in filter bed, head loss increased for all filter columns except for filter d_{10} 0.26 mm. By performing the linear regression analysis, it was found out that the slope values were significantly different from zero for all filter columns. This result indicated that gradual changes in the solids load were responsible for the development of head loss. Compared to other filter columns, filter d_{10} 0.26 mm was the most stable filter in regard to the alteration of hydraulic conductivity toward the addition of solids. It indicates that filter d_{10} 0.26 mm would have the longest filter run among others. By taking the behavior of filter d_{10} 0.26 mm into consideration, the d_{10} of 0.26 mm was taken as the effective size of filter columns in the test of varied C_u in Phase I.

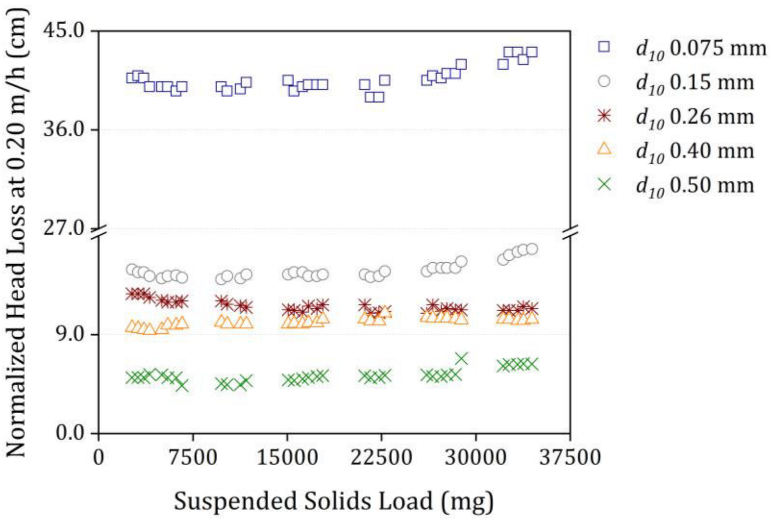


Figure 35. Phase I - Development of normalized head loss at 0.20 m/h of Set 1 in the test of varied d_{10}

5.2.2 Variation in C_u

Table 14. Phase I - Characteristics of filter columns in the test of varied C_u

Parameters	C_u 2.5	C_u 3	C_u 5
Initial Hyd. Cond. $k_{(0)}$ (m/s)			
Set A	3.72×10^{-4}	2.21×10^{-4}	2.78×10^{-4}
Set B	3.55×10^{-4}	2.61×10^{-4}	6.01×10^{-4}
Set C	4.00×10^{-4}	2.00×10^{-4}	4.72×10^{-4}
Initial Hyd. Loading Rate (m/h)			
Set A	0.22	0.21	0.23
Set B	0.21	0.21	0.22
Set C	0.20	0.21	0.21
Initial Δh (cm)			
Set A	9.6	16.2	12.8
Set B	10.0	13.5	6.2
Set C	8.3	17.6	7.8

Characteristics of filter columns from Set A, Set B and Set C were presented in Table 14. It was expected that the initial hydraulic conductivity of filter columns with wide graded sand would be lower because the pores might be filled up with the finer grains. However, based on the measurement, initial hydraulic conductivity of filter column with wide graded sand were higher than the values of filter column with narrow graded.

The results from this test on the turbidity and TSS removal did not confirm the results from the previous test in varied C_u in the Pre-Experiment Phase. The filter column with higher C_u in the Phase I could achieve turbidity and TSS removal as high as filter columns with the lower C_u. From the inlet quality of 100±10 NTU and 220 mg/L, outlet turbidity and TSS was found to be in average less than 2 NTU (see Figure 36) and 3 mg/L (see Figure 37) respectively for every column in all sets. All filter columns in Set A, Set B and Set C achieved a percentage of turbidity removal around 99.00 % (see Table 15).

Table 15. Phase I - Average turbidity and TSS removal in the test of varied C_u

Set	Turbidity Removal			TSS Removal		
	C_u 2.5	C_u 3	C_u 5	C_u 2.5	C_u 3	C_u 5
Set A	98.97 %	98.95 %	98.92 %	98.63 %	98.57 %	98.09 %
Set B	99.06 %	99.20 %	99.17 %	98.78 %	99.00 %	98.66 %
Set C	99.13 %	99.25 %	99.21 %	98.81 %	98.97 %	99.02 %

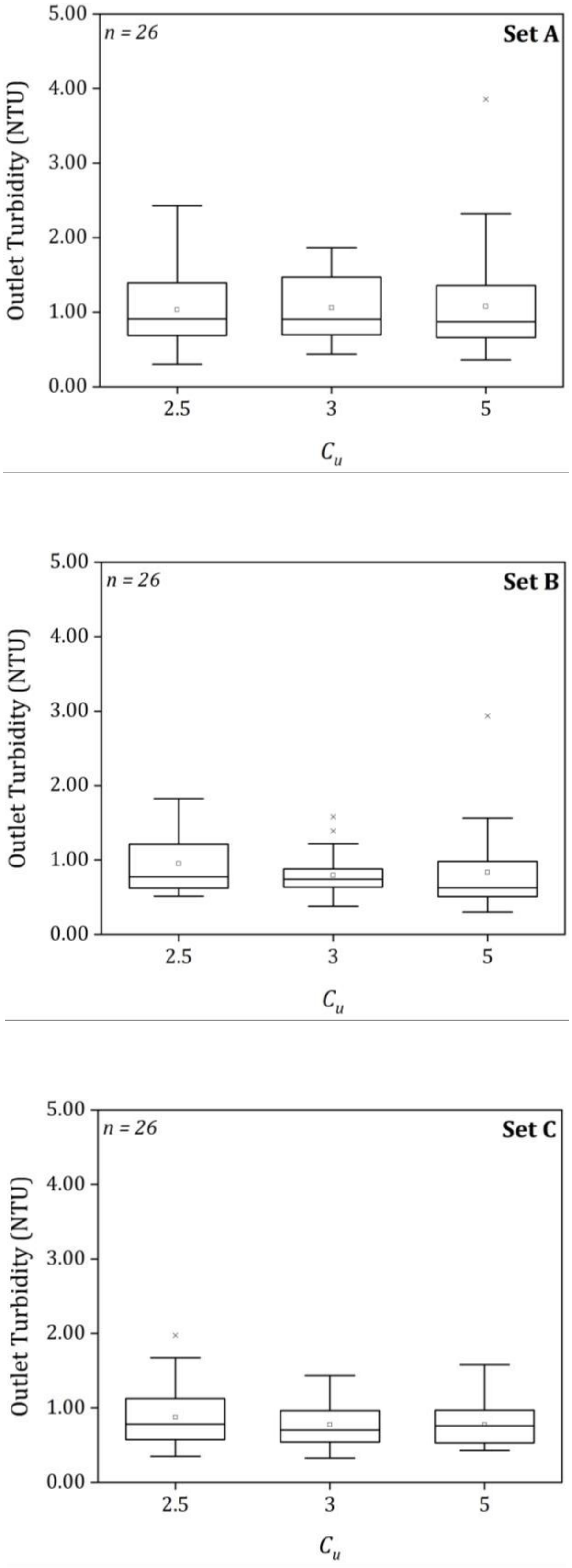


Figure 36. Phase I - Outlet turbidity of filter columns in the test of varied C_u

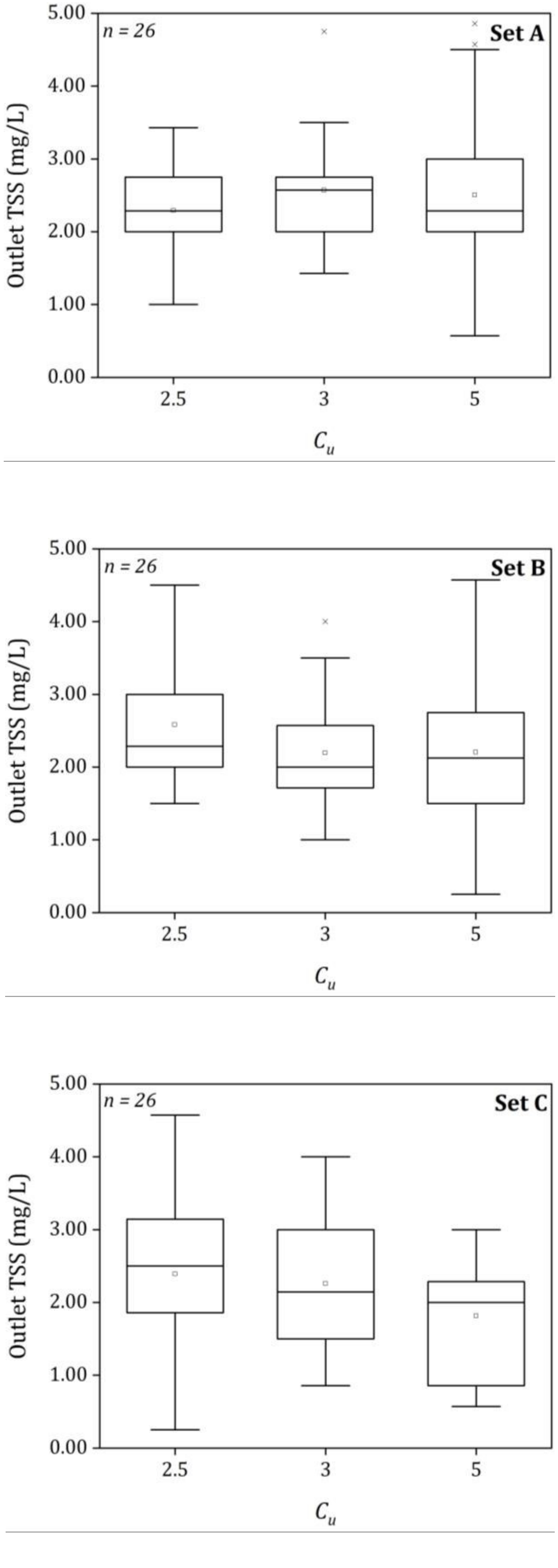


Figure 37. Phase I - Outlet TSS of filter columns in the test of varied C_u

In order to analyze whether there was a significant difference among filter columns in regard to the removal efficiency, ANOVA test was performed. It was found out that the mean values of outlet turbidity and TSS of all filter were not significantly different (Table 16) since the p-values were higher than the significance level of 0.05 in every set. These findings indicated that C_u did not influence significantly the turbidity and TSS removal.

Table 16. Phase I - Results of ANOVA test at significance level of 0.05 in the test of varied C_u

Set	p-value	
	Turbidity	TSS
Set A	0.9570	0.2145
Set B	0.3772	0.1431
Set C	0.4498	0.4783

Deposition of solids in the filter bed increased the resistance of the water to pass through hence altered the hydraulic conductivity. The more solids were retained, the lower the hydraulic conductivity should be. Figure 38 presents the changes in the average relative hydraulic conductivity from the three grain size distributions. All filter columns except filter C_u 3 in all set experienced the gradual decrease on hydraulic conductivity. After approximately 22,500 mg solids retained in filter bed, the initial hydraulic conductivity of filter C_u 2.5 and filter C_u 5 decreased up to 7 % and 18 % from the initial values respectively. At the end of filter run the hydraulic conductivity increased up to 19 % from the initial value in filter C_u 3. This increase might be caused by the released of the trapped air bubbles, the changing of the voids arrangement and on the pores connection.

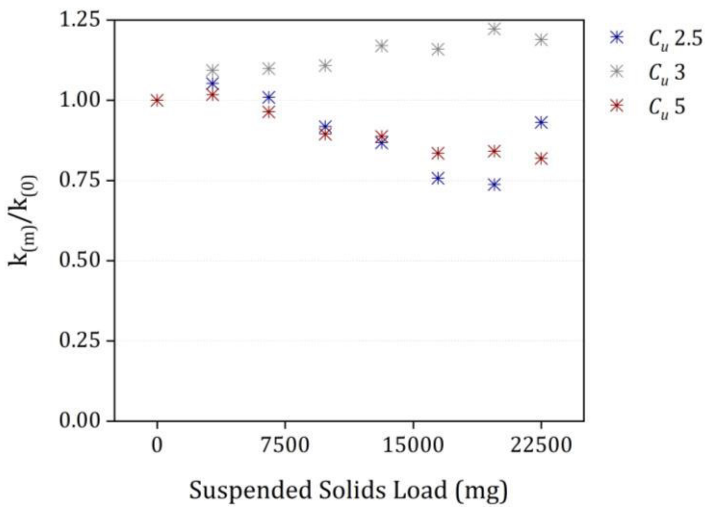


Figure 38. Phase I - Development of average relative hydraulic conductivity of filter columns in the test of varied C_u

With the addition of solids in the sand bed, average normalized head loss at 0.20 m/h increased for filter columns C_u 2.5 and C_u 5 and decreased for filter columns C_u 3 (see Figure 39). The increase of normalized head loss at 0.20 m/h for filter C_u 2.5 and filter C_u 5 was around 50 % and 31 % respectively. According to these findings, especially on the alteration of hydraulic conductivity and normalized head loss, it could be inferred that that filter columns with C_u of 2.5 tended to clog faster compared to other filter configurations. This finding confirmed the result of the previous test the pre-experiment phase (see Section 5.1.2) i.e. filter run time would be longer for a filter column with higher C_u. Since the capacity of all filter columns was still high (see Figure 38), they were continued to be operated to study the influence of high hydraulic loading rate on suspended solids removal.

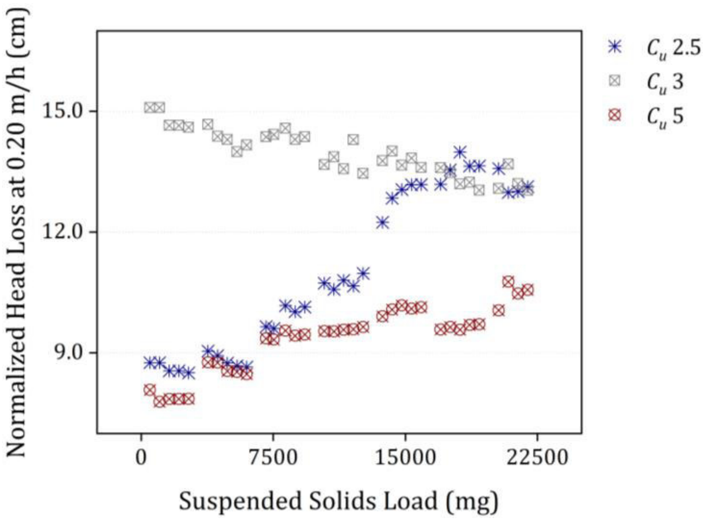


Figure 39. Phase I - Development of average normalized head loss at 0.20 m/h of filter columns the test of varied C_u

5.3 Influence of High Hydraulic Loading Rate on Suspended Solids Removal

When the filter operation under high hydraulic loading rate was started, approximately 22,500 mg of solids were already deposited in the filter bed. The existence of these solids influenced the behavior of filter columns not only in regard to their hydraulics but also in regard to the removal efficiencies. Table 17 presents the comparison of average filter efficiencies under low (0.20±0.05 m/h) and high (0.60±0.15 m/h) hydraulic loading rates. Turbidity and TSS removals of filter columns operated under high hydraulic loading rate were surprisingly higher than when they were operated under low rate. For both types of hydraulic loading rate, the filter columns were fed with the same inlet water quality i.e. 100±10 NTU and 220 mg/L. Under high rate, all filter columns were able to reduce the turbidity to below 0.50 NTU averagely (see Figure 40). This value was around 75 % lower than the average outlet turbidity of filter columns when they were operated under low hydraulic loading rate (see Figure 36). Based on the turbidity removal, filter columns NG-1 achieved the highest efficiency averagely. Meanwhile, filter columns NG-2 performed slightly lower than the others.

Table 17. Phase I - Average turbidity and TSS removal of filter columns operated under low (0.20±0.05 m/h) and high (0.60±0.15 m/h) hydraulic loading rate

Filter Columns	Turbidity Removal		TSS Removal	
	Low Rate	High Rate	Low Rate	High Rate
C_u 2.5	99.05 %	99.70 %	98.88 %	99.22 %
C_u 3	99.13 %	99.58 %	98.94 %	99.25 %
C_u 5	99.10 %	99.66 %	99.02 %	99.22 %

The percentage of TSS removal was averagely in the same range for all filter columns. Average outlet TSS dropped to below 2 mg/L after the filter columns were operated under high hydraulic loading rate (see Figure 41). This value was around 33 % lower than the average outlet concentration from the previous test (see Figure 37).

The measurement of size distribution of solids found in the outlet confirmed the previous results that filter columns with C_u of 2.5 were more capable on retaining fine solids than other columns (see **Error! Reference source not found.** and Appendix 4). From almost all sets, the average size of solids found in the outlet of filter columns C_u 2.5 was finer than of filter C_u 3 and filter C_u 5. It was also found out that the solids in the outlet of filter columns operated under high hydraulic loading rate were finer than under low hydraulic loading rate.

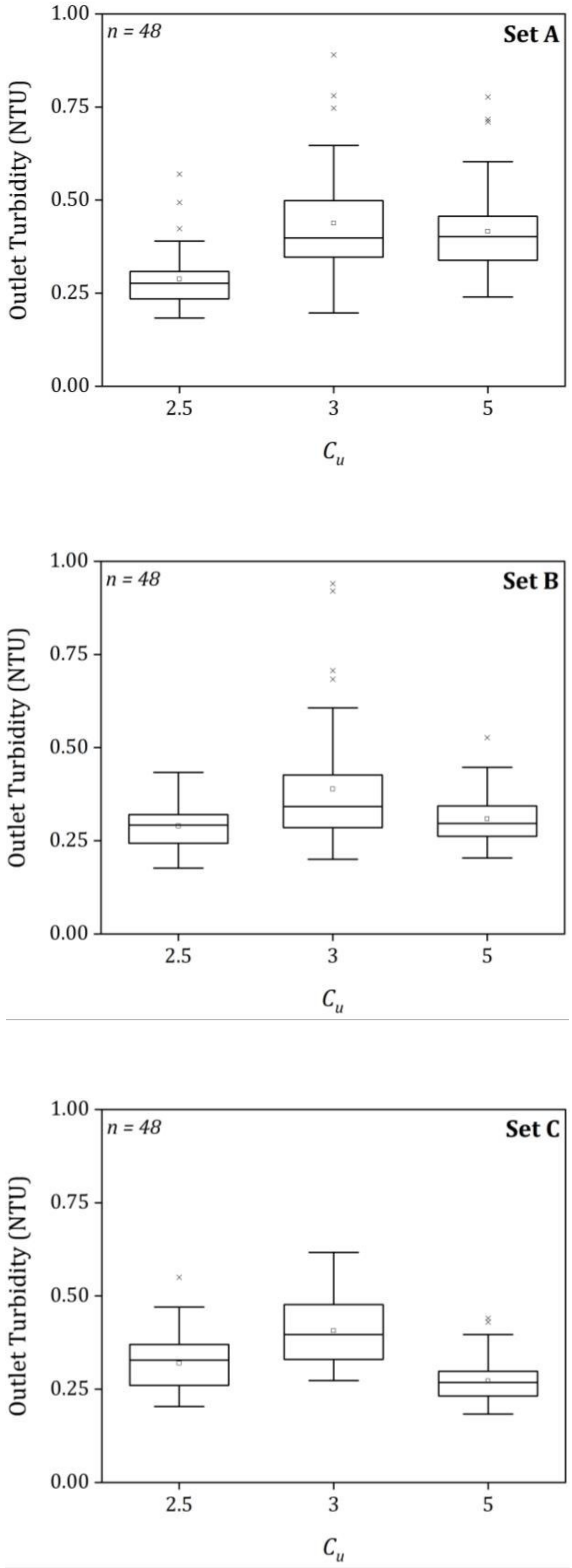


Figure 40. Phase I - Outlet turbidity of filter columns in test of high hydraulic loading rate (0.60±0.15 m/h)

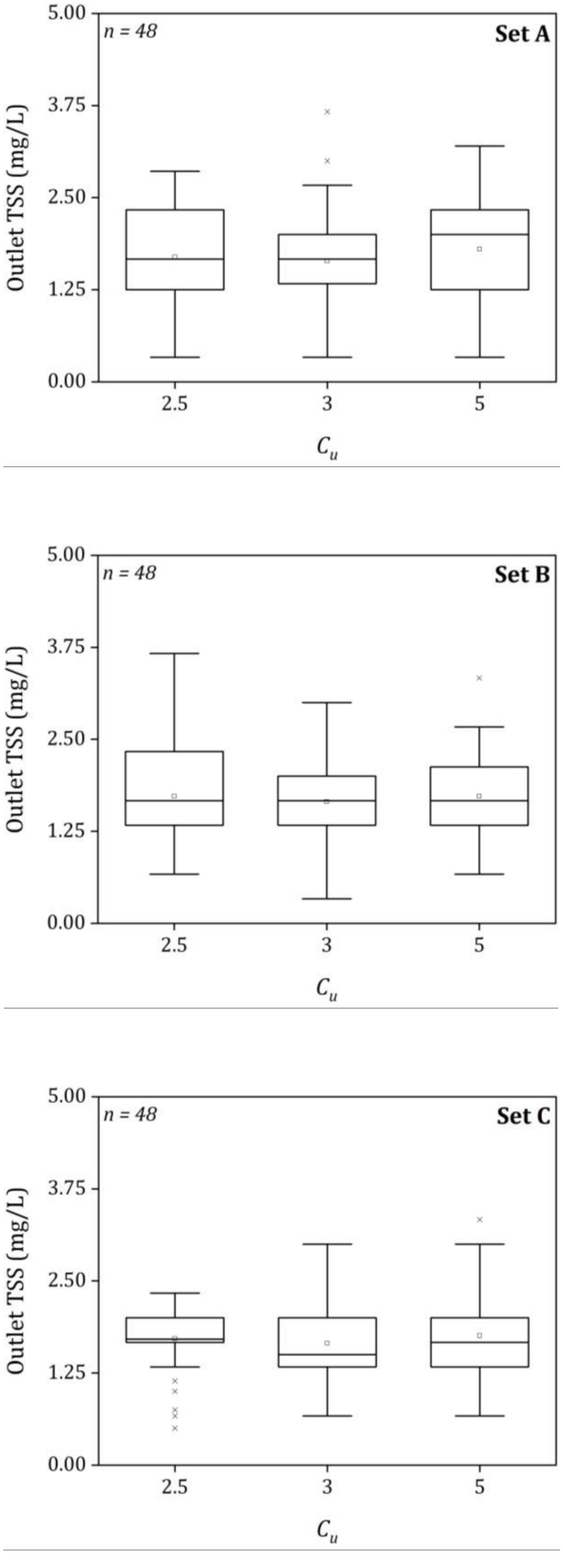


Figure 41. Phase I - Outlet TSS of filter columns in the test of high hydraulic loading rate (0.60±0.15 m/h)

Changes in the hydraulic conductivity of filter columns toward the addition of solids were observed during the operation (see Figure 42). During the filter operation under low rate, an anomaly occurred in the filter columns C_u 3. In all sets, the hydraulic conductivity of filter C_u 3 increased while the other filter columns decreased with the addition of solids. In the filter operation under high hydraulic loading rate, average hydraulic conductivity decreased up to 44 % and 21 % for filter C_u 2.5 and filter C_u 5. Meanwhile, in filter C_u 3, an increase of 3 % on the hydraulic conductivity was found.

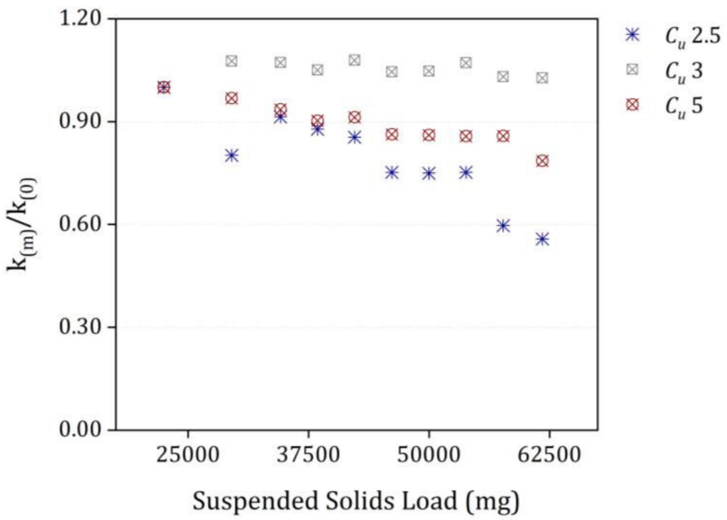


Figure 42. Phase I - Development of average relative hydraulic conductivity of filter columns in the test of high hydraulic loading rate (0.60±0.15 m/h)

Compensating the decrease on the hydraulic conductivity, the head loss in the filter bed was gradually increased except for filter columns C_u 3 (see Figure 43). Following the pattern of hydraulic conductivity, suspended solids load affected the development of head loss predominantly in the filter columns C_u 2.5 and C_u 5. After the filter operation was terminated, the average value of the final head loss increased around 57 % and 23 % from the initial values for filter columns C_u 2.5 and C_u 5 respectively. Meanwhile, the effect of suspended solids load in the filter columns C_u 3 was minor. The average increase of final head loss in filter columns C_u 3 was only 2 % from the initial values. As expected, the increase of head loss in filter with C_u of 2.5 was higher compared to the other configurations.

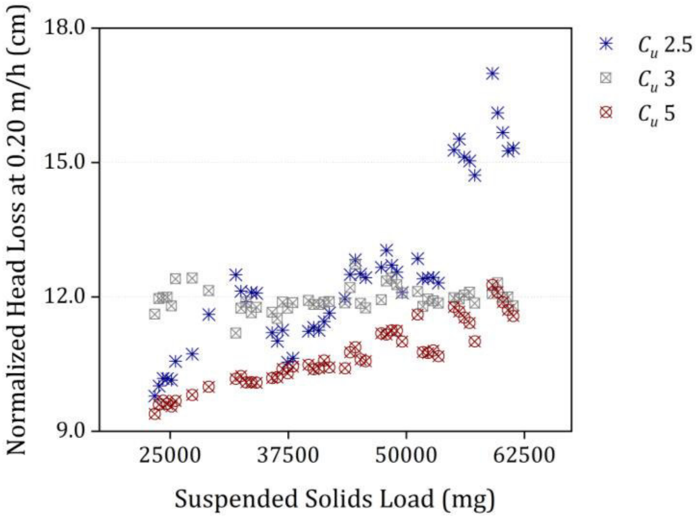


Figure 43. Phase I - Development of average normalized head loss at 0.20 m/h of filter columns in the test of high hydraulic loading rate (0.60±0.15 m/h)

Figure 44 presents the behavior of filter columns toward the total solids load from the beginning of filter operation until the termination under high hydraulic loading rate. Hydraulic conductivity of filter C_u 2.5 dropped up to 48 % from the initial value. It indicated that after a load of around 62,500 mg solids the filter capacity declined to almost 50 % from its actual capacity. The same decreasing trend occurred in filter C_u 5 which experienced a decrease of 36 %. Filter C_u 3 behaved differently due to the increase of hydraulic conductivity up to 22 % from its initial. By considering both the development of relative hydraulic conductivity and normalized head loss at 0.20 m/h, it could be inferred that the filter columns with C_u of 2.5 tended to clog faster than the others.

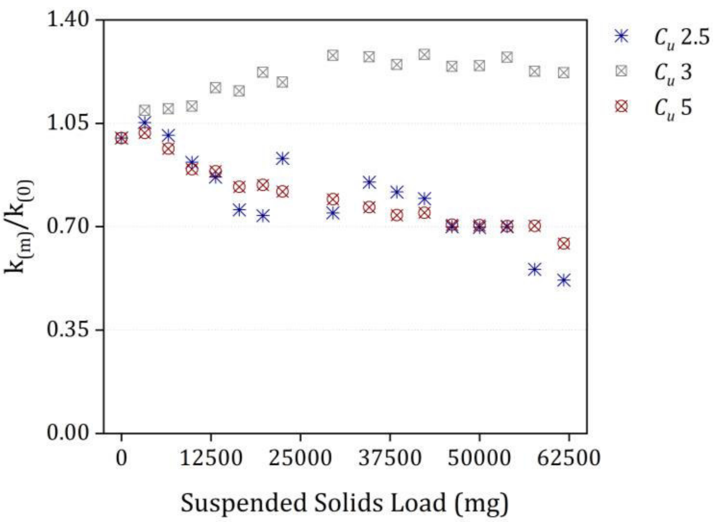


Figure 44. Phase I - Development of average relative hydraulic conductivity of filter columns from the clean filter bed until the termination of the operation at 0.60±0.15 m/h

5.4 Influence of the Grain Size Distribution on Solids Penetration in Filter Bed

5.4.1 Variation in d_{10}

Table 18 lists the characteristics of five filter columns which were tested in this phase. The initial hydraulic conductivity was as expected where the values were higher for coarser media. However, the hydraulic conductivity of filter Coarse-4 was slightly lower than filter Coarse-3.

Table 18. Phase II - Characteristics of filter column in the test of varied d_{10}

Parameters	d_{10} 0.075 mm	d_{10} 0.26 mm	d_{10} 0.50 mm	d_{10} 0.70 mm	d_{10} 0.90 mm
Initial Hyd. Conductivity $k_{(0)}$ (m/s)	8.22×10^{-5}	2.71×10^{-4}	4.72×10^{-4}	2.96×10^{-3}	2.87×10^{-3}
Initial Hyd. Loading Rate (m/h)	0.44	0.47	0.48	0.40	0.42
Initial Δh (cm)	41.0	11.7	7.0	1.0	1.0

According to the results presented in Section 5.2, there was no significant difference on the filter performance of filter columns with fine and coarse sand, especially on the turbidity removal. This insignificant difference was proved by the result of the ANOVA test. On the other hand, the experiment in Phase II showed that the turbidity and TSS removal decreased with the increase of d_{10} (see Figure 45 and Figure 46). The turbidity was reduced from 45±5 NTU to below 1 NTU averagely even in the filter columns with very coarse media. This average value of outlet turbidity met the requirement of WHO in regard to the water quality for achieving an effective disinfection. Average percentages of turbidity removal were 99.44 %, 99.36 %, 99.00 %, 98.39 % and 97.89 % for filter columns d_{10} 0.075 mm, d_{10} 0.26 mm, d_{10} 0.50 mm, d_{10} 0.70 mm and d_{10} 0.90 mm respectively. Concentration of TSS found in the outlet was averagely below 2 mg/L from the inlet concentration of 110 mg/L. Filter d_{10} 0.075 mm achieved the highest TSS removal i.e. 99.18 % followed by filter columns d_{10} 0.26 mm (99.03 %), d_{10} 0.50 mm (98.87 %), d_{10} 0.70 mm (98.66 %) and d_{10} 0.90 mm (98.53 %).

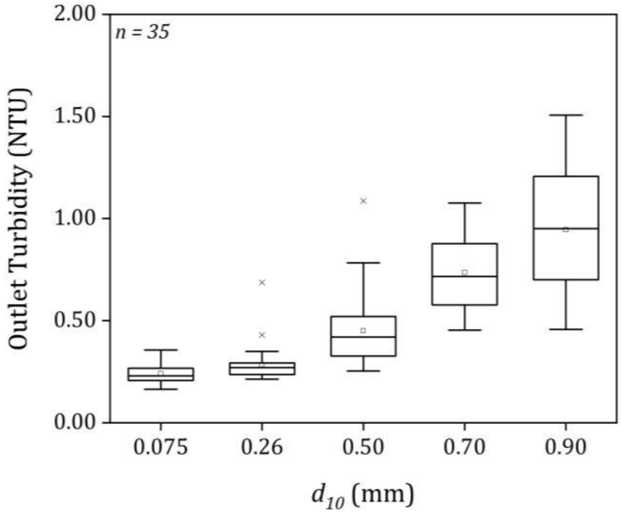


Figure 45. Phase II – Outlet turbidity of filter columns in the test of varied d_{10}

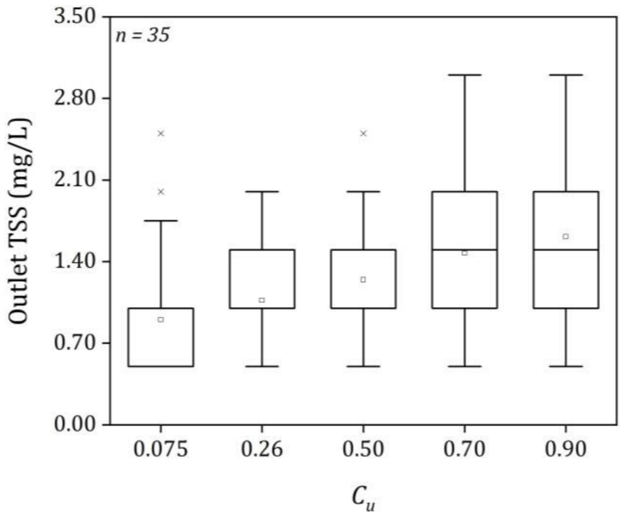


Figure 46. Phase II – Outlet TSS of filter columns in the test of varied d_{10}

Although the five filter columns achieved high efficiencies, the difference of average outlet turbidity and TSS between fine and coarse media was quite significant. Average outlet turbidity of filter column d_{10} 0.075 mm was 0.24 NTU which was nearly four times lower than the average outlet turbidity of filter d_{10} 0.90 mm (0.95 NTU). In the case of TSS, the average outlet concentration of filter column d_{10} 0.075 mm was 0.85 mg/L. Meanwhile, the filter column d_{10} 0.90 mm had the average outlet concentration of 1.61 mg/L which was nearly two times the outlet of filter d_{10} 0.075 mm. Based on this result, the argument of using finer sand to ensure high slow sand filtration performance was confirmed. However, it is worth noting that the coarser d_{10} tested in this study was nearly three times greater than the upper limit of the recommended values (see Table 1).

During the filter operation, the hydraulic conductivity of filter columns was altered with the deposition of solids in filter bed (see Figure 47). The changes in filter capacity could be used to predict the clogging pattern of filter columns. Filter d_{10} 0.075 mm contained the finest media and the initial hydraulic conductivity was the lowest among others. At the end of the filter operation, filter d_{10} 0.075 mm experienced the highest decrease of hydraulic conductivity i.e. 54 % followed by filter d_{10} 0.26 mm with a decrease of 51 %.

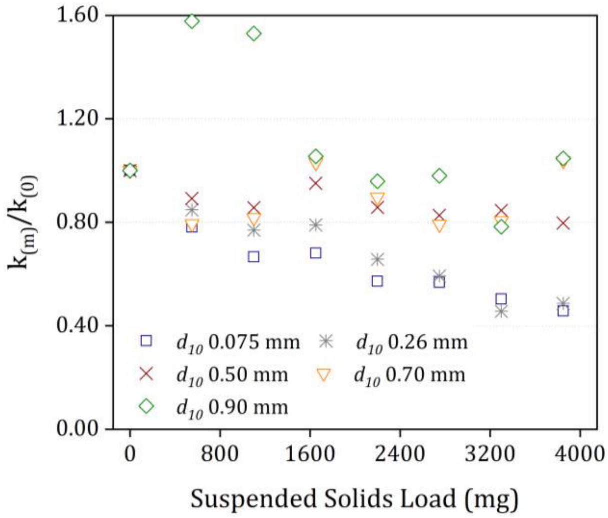


Figure 47. Phase II - Development of relative hydraulic conductivity of filter columns in the test of varied d_{10}

Clogging period can be predicted from the development of relative hydraulic conductivity and the increase of normalized head loss at 0.20 m/h (Figure 48). The changes of filter capacity on filter d_{10} 0.70 mm and filter d_{10} 0.090 mm were not as predominant as in the filter with finer media. Filter d_{10} 0.70 mm and filter d_{10} 0.90 mm behaved differently from others toward the solids load. While the hydraulic conductivity of filter d_{10} 0.075 mm, filter d_{10} 0.26 mm and filter d_{10} 0.50 mm decreased with the solids load, filter columns d_{10} 0.70 mm and d_{10} 0.90 mm slightly increased up to around 4 % and 5 %.

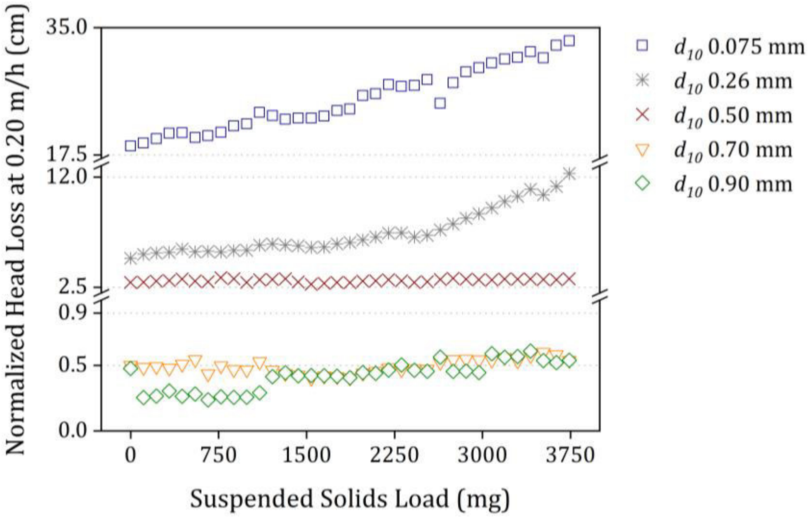


Figure 48. Phase II - Development of normalized head loss at 0.20 m/h of filter columns on the test of varied d_{10}

Before the sand bed was scraped, filter cake was observed to be established notably in columns with fine filter media and a thin layer was found in filter with d_{10} of 0.50 mm (see Appendix 9). Turbidity measurement of the scraped sample validated this observation (see Figure 49). This filter cake formation caused a great hydraulic conductivity decrease and a considerable head loss increase of the filter d_{10} 0.075 mm and filter d_{10} 0.26 mm.

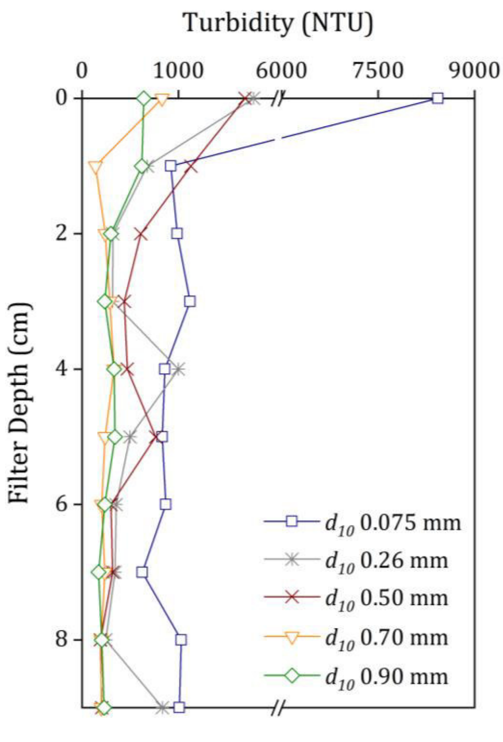


Figure 49. Phase II - Solids penetration in filter columns in the test of varied d_{10}

Turbidity values of the first 1 cm sand layer were decreased with the increase of d_{10}. From the filter d_{10} 0.075 mm and filter d_{10} 0.26 mm, the turbidity values dropped considerably on the second 1 cm sand layer. Meanwhile, in the filter d_{10} 0.50 mm the turbidity value decreased gradually and became more or less stable below 3 cm sand layer. In the two coarse filter columns, the turbidity value did not decrease significantly from the first 1 cm sand layer to lower depth indicating a deeper penetration of solids. In this test, the coarse filter media did not contain any clay and silt fraction.

Microscopic visualization of sand sample (see Figure 50) shows that suspended solids indicated by dark cloud among the grains are abundant in the top layer compared to the lower layer. Suspended solids mass was estimated based on the total mass of sand sample from the first 1 cm layer as a representative. Mass of suspended solids from filter columns d_{10} 0.075 mm, d_{10} 0.50 mm and d_{10} 0.70 mm are presented in Table 19. For fine media formation of filter cake was the dominant mechanism on suspended solids removal represented by high percentage removal at the first 1 cm of filter bed. Meanwhile, deeper straining tends to be the dominant removal mechanism in the coarser media.

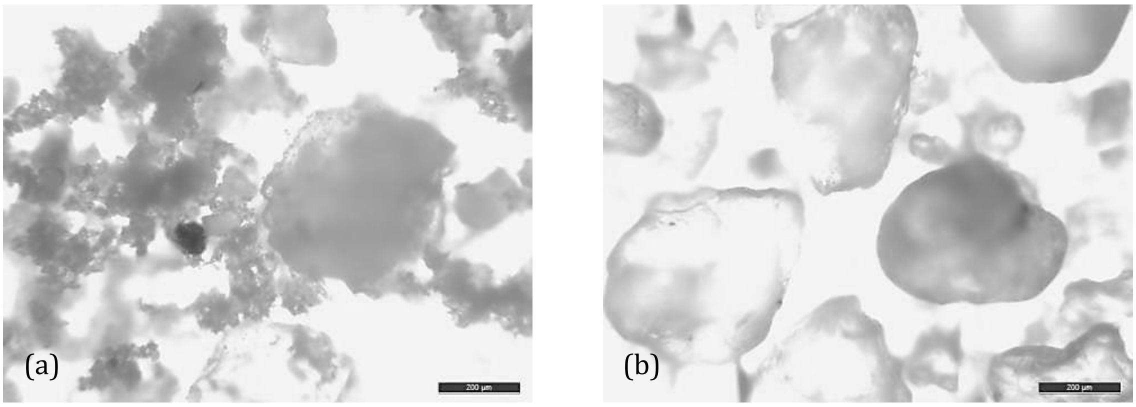


Figure 50. Phase II - Microscopic visualization of top layer i.e. first 1 cm (a) vs lower layer i.e. 10 cm below surface (b) from filter column with d_{10} of 0.26 mm

Table 19. Phase II - Percentage of suspended solids mass retained at the first 1 cm of filter bed in the test of varied d_{10}

Filter Columns	Mass Retained (mg)	% Removal at Surface of Filter Bed
d_{10} 0.075 mm	3,498	90.87
d_{10} 0.50 mm	1,865	48.43
d_{10} 0.70 mm	1,240	16.10

5.4.2 Variation in C_u

According to the characteristics of filter columns (see Table 20), filter C_u 7 had the highest hydraulic conductivity value confirming the previous result in Section 5.2.2. This can be explained due to the composition of sand size (see Table 4) within the filter column. Filter C_u 7 consisted of higher coarse fraction compared to the others.

Table 20. Phase II - Characteristics of filter columns in the test of varied C_u

Parameters	C_u 2.5	C_u 3	C_u 7
Initial Hydraulic Conductivity $k_{(0)}$ (m/s)	2.73×10^{-4}	3.27×10^{-4}	3.71×10^{-4}
Initial Hydraulic Loading Rate (m/h)	0.20	0.20	0.22
Initial Δh (cm)	4.8	4.1	3.8

Removal of turbidity in this test was satisfactory for all filter columns. Filter C_u 2.5, achieved the highest percentage removal 99.68% followed by filter C_u 3 with 99.52% and filter C_u 7 with 99.45% (Figure 51). This result confirmed the turbidity removal of filter columns in the Pre-Experiment Phase (see Section 5.1.2). Average outlet turbidity for all filter columns was <0.60 NTU. Related to TSS removal, filter C_u 2.5 was also found out to perform slightly better compared to the other two columns. Removal percentage of filter C_u 2.5 was 99.66% while filter C_u 3 and filter C_u 7 were 99.58% and 99.51% respectively (Figure 52).

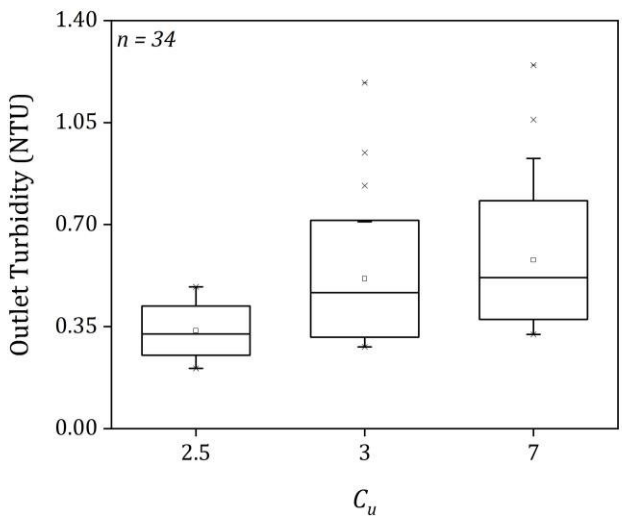


Figure 51. Phase II - Outlet turbidity of filter columns in the test of varied C_u

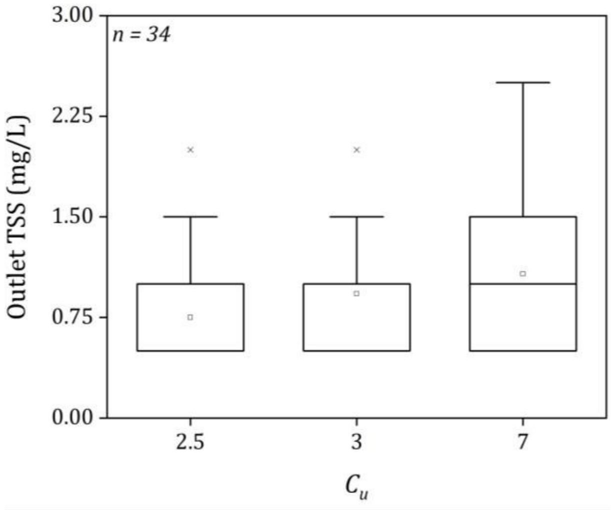


Figure 52. Phase II - Outlet TSS of filter columns in the test of varied C_u

Gradual decrease on hydraulic conductivity with suspended solids load was observed on the whole filter columns. According to the development of the relative hydraulic conductivity (see Figure 53), the behavior of filter C_u 3 and filter C_u 7 was similar toward the addition of solids in the sand bed where both filter columns declined rapidly until the load of 3,000 mg solids. After that, the decrease was slightly until the filter operation was terminated. Filter C_u 2.5 experienced a gradual decrease of hydraulic conductivity. At the end of the filter operation, the hydraulic conductivity decreased more or less in the same rate i.e. 89 % for filter C_u 2.5 and filter C_u 7 and 88 % for filter C_u 3. By considering the trend of the declination, filter C_u 2.5 tended to clog faster than the other two columns. This result confirmed the finding of Pre-Experiment Phase (see Section 5.1.2) and Phase I (see Section 5.4.2) where the media with lower C_u tended to experience faster clogging period.

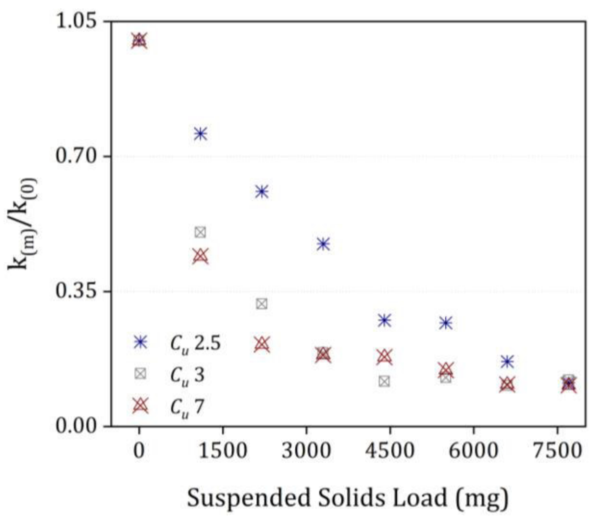


Figure 53. Phase II - Development of relative hydraulic conductivity of filter columns in the test of varied C_u

Based on the analysis of solids penetration (Figure 54), turbidity of first 1 cm sand sample was very high followed by a sudden decrease for lower depth. High turbidity values found in the whole filter columns indicated that the dominant removal mechanism was the formation of filter cake. The presence of filter cake on the filter bed was responsible for the significant decrease of hydraulic conductivity in all filter columns.

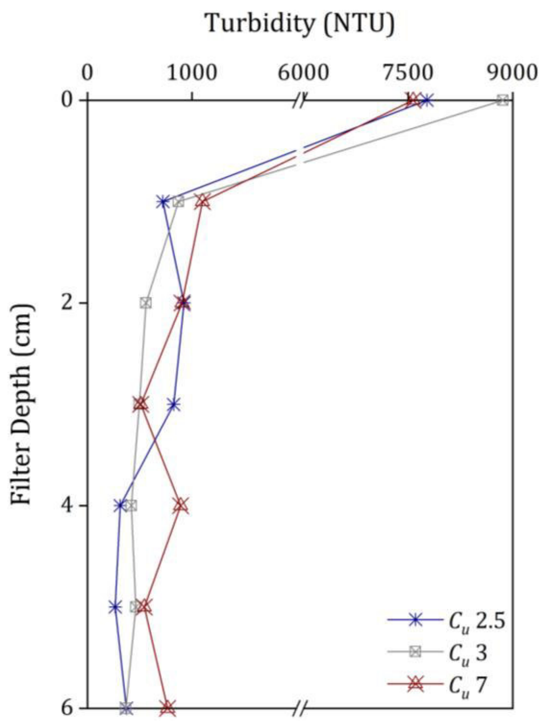


Figure 54. Phase II - Solids penetration in filter columns in the test of varied C_u

5.5 Influence of Hydraulic Loading Rates on Solids Penetration in Filter Bed

Uncontrolled grains and voids arrangement in the filter bed resulted in the different values of porosity and void ratio which at the end affected the initial hydraulic conductivity (see Table 21). Filter 0.08 m/h, as estimated, had the lowest initial hydraulic conductivity compared to others. As a consequence, the Δh of filter 0.08 m/h was higher than filter 0.20 m/h although the first filter was operated under a hydraulic loading rate that was more than a half lower than the second filter.

Table 21. Phase II - Characteristics of filter columns in the test of influence of hydraulic loading rate

Parameters	0.08 m/h	0.20 m/h	0.80 m/h
Initial Hydraulic Conductivity $k_{(0)}$ (m/s)	9.03×10^{-5}	2.73×10^{-4}	2.55×10^{-4}
Initial Hydraulic Loading Rate (m/h)	0.08	0.20	0.76
Initial Δh (cm)	6.0	4.8	19.1

As expected, the percentage of turbidity removal was higher with the lower hydraulic loading rate. Highest average removal was achieved by filter 0.08 m/h with 99.72% followed by filter 0.20 m/h with 99.68% and filter 0.80 m/h with 99.19% (see Figure 55). Average outlet turbidity of High-1 was almost three times higher than from Low-1. However, the average outlet turbidity for all filter columns was still below 1 NTU.

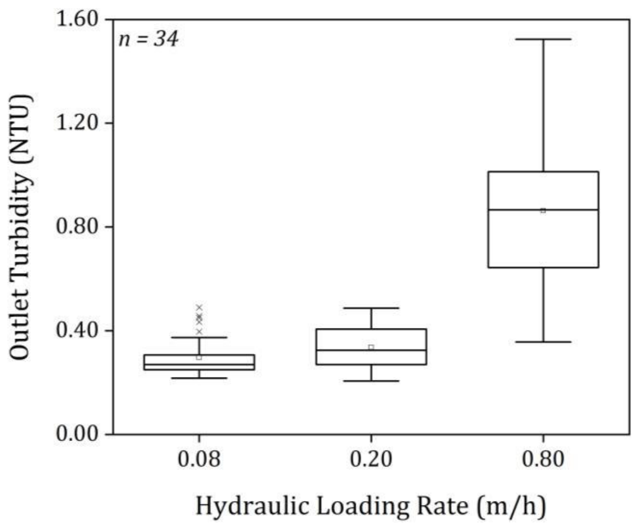


Figure 55. Phase II - Outlet turbidity of filter columns operated under different hydraulic loading rate

Related to the TSS removal, the same pattern was applied. The lower the hydraulic loading rate, the higher the percent removal is (see Figure 56). By operating the filter under 0.08±0.02 m/h and 0.20±0.05 m/h, average TSS removal reached 99.66%. Concentration of TSS in the outlet for filter 0.08 m/h and filter 0.20 m/h was below1 mg/L while for filter 0.80 m/h was above1 mg/L. The filter column operated under 0.8±0.2 m/h achieved 99.33% TSS removal.

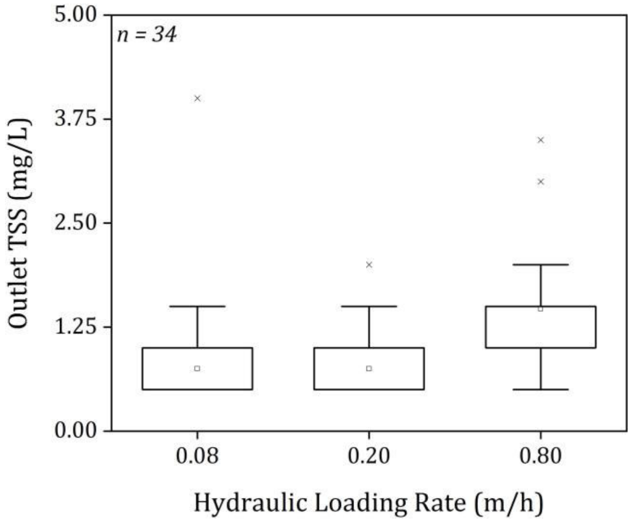


Figure 56. Phase II - Outlet TSS of filter columns operated under different hydraulic loading rate

At the end of the filter operation, hydraulic conductivity declined significantly for filter columns 0.08 m/h (92 %) and 0.20 m/h (89 %). In filter column 0.80 m/h, decrease of hydraulic conductivity was only 43 %. The hydraulic conductivity of filter column 0.08 m/h decreased considerably until the load of 4,500 mg solids and then slightly until the termination of filter operation (see Figure 57). As a consequence of the prevailing decrease of filter 0.08 m/h, the normalized head loss at 0.20 m/h increased considerably (see Figure 58). In the filter column 0.20 m/h, the hydraulic conductivity decreased gradually with the solids load. Filter 0.80 m/h behaved differently as the hydraulic conductivity decrease was linear with the solids load.

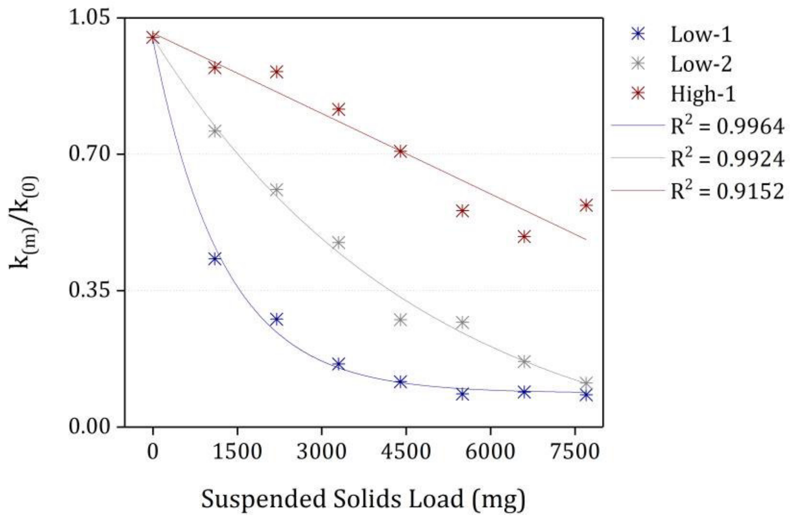


Figure 57. Phase II - Development of relative hydraulic conductivity of filter columns operated under different hydraulic loading rate

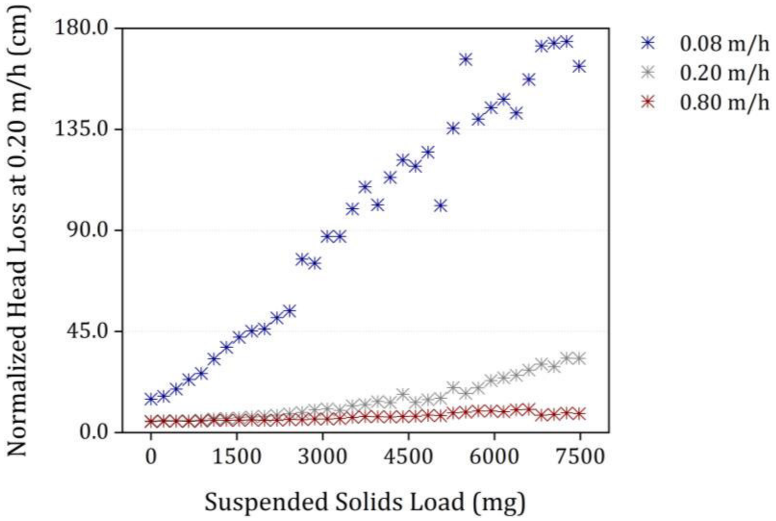


Figure 58. Phase II - Development of normalized head loss at 0.20 m/h of filter columns operated under different hydraulic loading rate

The different behavior of filter columns towards the solids load could be described by considering the solids penetration. According to the turbidity measurement from the sand sample, filter 0.08 m/h had the highest value on the first 1 cm scraping (see Figure 59). This high value was followed by a sudden decrease to <1000 NTU. Having lower turbidity value from the first 1 cm of sand sample, filter 0.20 m/h also experienced a sudden decrease in the lower bed depth. Those values indicated that most of the suspended solids retained at the top of filter bed causing significant decrease on hydraulic conductivity and increase in head loss. Meanwhile in filter 0.80 m/h, it was found out that the solids penetrated deeper within the filter columns by considering the turbidity values of first and second 1 cm of sand samples. Therefore, the decrease of hydraulic conductivity and increase of normalized head loss were not as high as in the filter columns with lower hydraulic loading rates. Deeper straining in filter 0.80 m/h was found to be higher compared to the filter 0.08 m/h and filter 0.20 m/h. If the feeding of filter column was extended, at certain point the decrease pattern of hydraulic conductivity of filter 0.80 m/h might be as the same as the pattern of filter columns 0.08 m/h and 0.20 m/h which likely to be exponential.

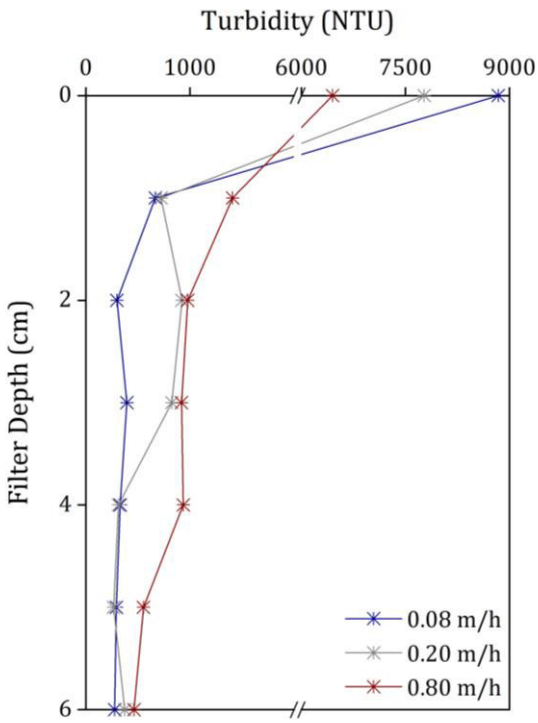


Figure 59. Phase II - Solids penetration in filter columns operated under different hydraulic loading rate

5.6 Increasing Filter Run Time by Applying Protection Layer

According to Mälzer and Gimbel (2006), protection layer applied in the filter columns may inhibit the clogging period and prolonging the filter run time. Two filter columns with the characteristics listed in Table 22 were tested in this phase to evaluate this method of Mälzer and Gimbel (2006). The initial hydraulic conductivity of filter column with protection layer was expected to be lower than without protection layer. However, based on the measurement, filter column WPL had a slightly higher hydraulic conductivity than filter WOPL.

Average turbidity removal of both filter columns was similar i.e. 99.68 % and 99.67 % for filter columns WOPL and WPL respectively (see Figure 60). The average values of outlet turbidity were 0.34 NTU for filter column without protection layer and 0.35 NTU for filter column with protection layer. Related to the average removal of TSS (see Figure 61), filter column WOPL (99.66 %) had slightly higher removal efficiency than filter column WPL (99.55 %).

Table 22. Phase II - Characteristics of filter columns to test the method of filter run time prolongation

Parameters	WOPL	WPL
Initial Hydraulic Conductivity $k_{(0)}$ (m/s)	2.73×10^{-4}	3.17×10^{-4}
Initial Hydraulic Loading Rate (m/h)	0.20	0.20
Initial Δh (cm)	4.8	4.7

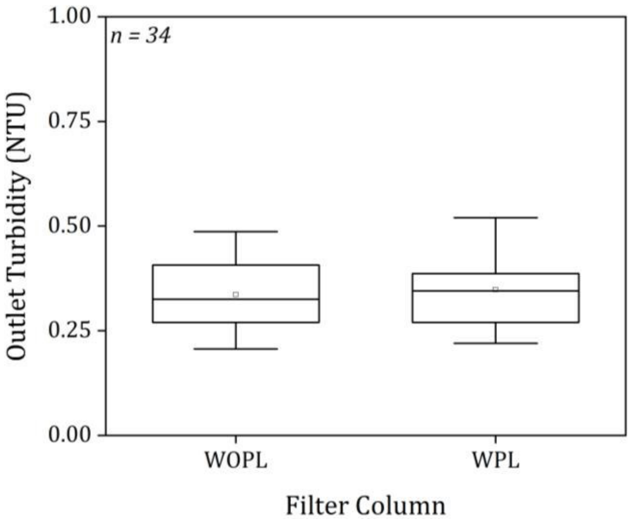


Figure 60. Phase II - Outlet turbidity of filter columns without and with protection layer

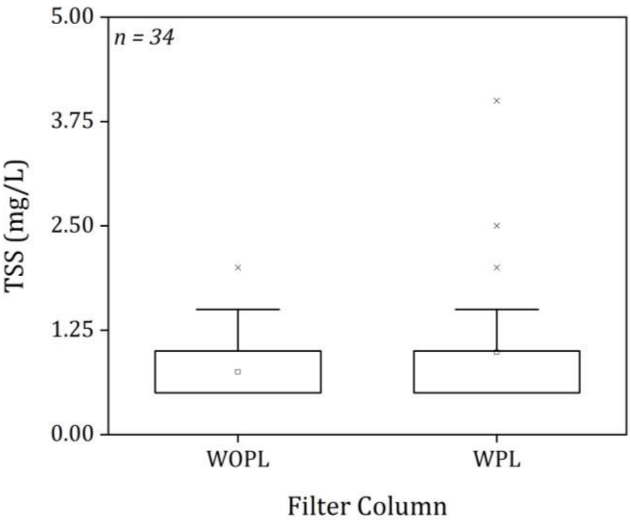


Figure 61. Phase II - Outlet TSS of filter columns without and with protection layer

Hydraulic conductivity decreased significantly for filter column without protection layer with the addition of solids in filter bed (see Figure 62). Decrease of hydraulic conductivity in filter WOPL was up to 89 % while in filter WPL, the decrease was only 26 %. This phenomenon led to the significant changes of the normalized head loss at 0.20 m/h in the filter column without protection layer (see Figure 63). These discrepancies on the developments of the relative hydraulic conductivity and normalized head loss at 0.20 m/h were because the gravel layer acted as the first strainer for the suspended solids. Filter cake was formed on the surface of sand bed in WOPL. Meanwhile, in filter column WPL, it was observed that some solids were retained in the gravel layer as could be identified from the solid penetration in Figure 64.

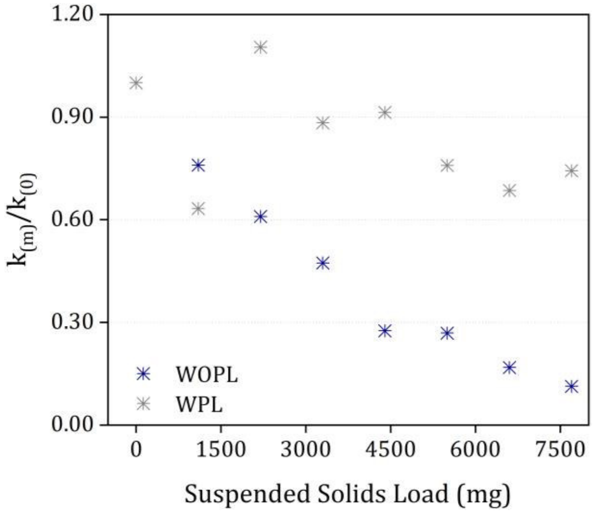


Figure 62. Phase II - Development of hydraulic conductivity filter columns without and with protection layer

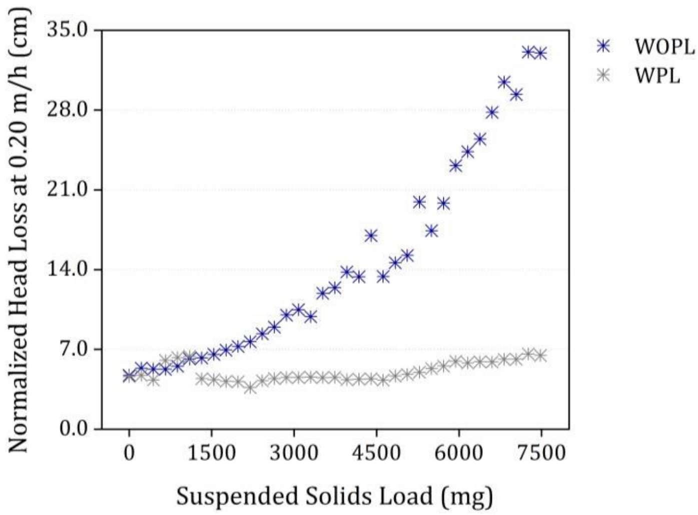


Figure 63. Phase II - Development of normalized head loss at 0.20 m/h filter columns without and with protection layer

In the solids penetration graph, the first value for WPL was obtained from the scraping of protection layer. The high turbidity value showed that some solids were retained in the protection layer. The scraping of first 1 cm of sand layer from filter WPL resulted in the significantly lower turbidity value than from filter WOPL. Since some solids were retained in the protection layer, the formation of filter cake might be retarded and the clogging could be decelerated.

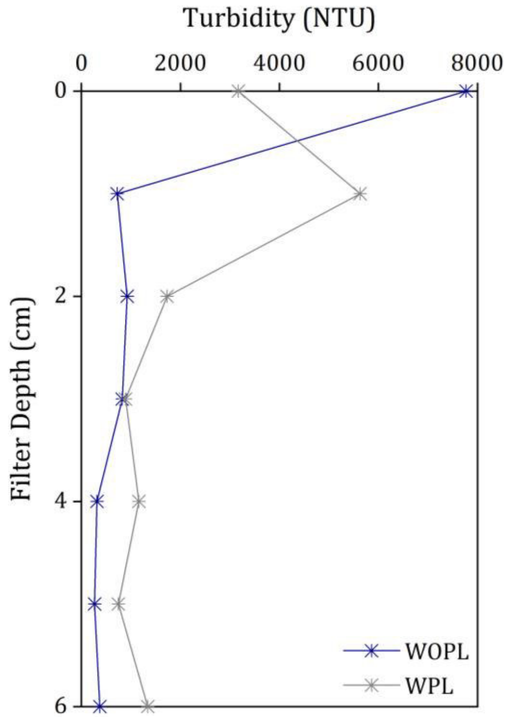


Figure 64. Phase II - Solids penetration in the filter columns without and with protection layer

6 Discussion

6.1 Optimization of Slow Sand Filtration Design

Generally, the results of this study not only showed the effectiveness of slow sand filter on removing the suspended solids but also proved that the ranges of the current recommended values of design criteria were too narrow. These narrow ranges contribute to the limitation on the optimization and wider utilization of the technology. In this study, the influence of each operating variable on the suspended solids removal, solids penetration and clogging period was investigated systematically so that the main purpose i.e. optimization on the design recommendation could be achieved.

In Phase I, it was found out that the d_{10} of filter media can be raised up to 0.50 mm without deteriorating the removal efficiency of suspended solids. According to the ANOVA test, the outlet turbidity values of the filter columns with d_{10} of 0.50 mm were not significantly different from the outlet turbidity of filter columns with finer media. Previously, Jenkins *et al.* (2011) also reported that the effect of grain size distribution (i.e. d_{10} 0.17 mm/C_u 2.4 and d_{10} 0.52 mm/C_u 2.1) on the turbidity removal by intermittent slow sand filtration was insignificant. Prior to Jenkins *et al.*, Langenbach (2010) also found the same result at the two newest studies (see Section 2.7.1). These findings strengthened the indication that the recommended values of d_{10} i.e. 0.15 – 0.35 mm is rather conservative. By using coarser media represented by d_{10} 0.50 mm, it is not only that the high removal efficiency can be obtained but also the capital cost to procure the sand can be reduced.

Since the d_{10} range tested in Phase I (0.075 – 0.50 mm) could not give the answer yet to how the d_{10} influences the suspended solids removal, coarser sand represented by d_{10} of 0.70 mm and 0.90 mm were tested in Phase II. Three other d_{10} values tested in Phase II were taken from the values in previous experiment i.e. d_{10} of 0.075 mm which represented extreme fine media, d_{10} of 0.26 mm which represented the recommended value and d_{10} 0.50 mm which represented the coarsest media in Phase I.

The results from Phase II confirmed that the coarser the filter media the lower the removal efficiency of suspended solids. However, the range of tested d_{10} values so that the confirmation could be proved was very broad i.e. 0.075 – 0.90 mm. The highest d_{10} value tested was almost three times higher than the upper limit of the recommended d_{10} value which is 0.35 mm. The average values of outlet turbidity of filter columns with coarser media represented by d_{10} of 0.50 mm, 0.70 mm and 0.90 mm were reaching more than one and a half, two and a half and three times the average of filter columns with recommended d_{10} of 0.26 respectively. However, the average turbidity values for all filter columns with coarser media tested in Phase II were still below 1 NTU. According to WHO, after the treatment with slow sand filtration, outlet turbidity should never exceed 5 NTU to achieve an effective disinfection process (WHO, 2017). Hence, average outlet quality from both finer and coarser media investigated in this study met the requirement of WHO.

From the perspective of suspended solids removal, employing coarser media did not lower the filtrate quality. However, in regard to the removal mechanism, coarse media contributed significantly to the deeper penetration of solids. According to the investigation, the coarser the media the deeper the penetration of solids is. In the filter columns with finer media, the pores size was too small for the solids to pass through. Therefore, the solids were retained on the surface of filter bed forming a layer so called filter cake. In this layer, which was actually an accumulation of very fine particles, the pores size was very small inhibiting the other solids to pass through. Therefore, the filter cake became a secondary filter layer. Formation of filter cake in the filter column with d_{10} of 0.075 mm occurred because most of the solids retained on the surface of filter bed, i.e. 91 % of total solids mass. On the contrary, formation of filter cake did not occur yet in filter column with d_{10} of 0.70 mm because the solids retained at the first 1 cm of sand layer were only around 16 % of total solids load and deeper straining became the dominant removal mechanism.

As the consequence of the type of removal mechanisms, the decrease of filter capacity was also different between the fine and coarse media. By the formation of filter cake, the characteristics of the filter were no longer affected by the grain size distribution of the media. The hydraulic conductivity of filter bed was determined by this layer. Therefore, in the filter columns with fine media i.e. Fine-1.1 and Fine-3.1 the hydraulic conductivity decreased significantly at the end of filter run. These hydraulic conductivity decreased caused the increase of head loss in filter columns with fine media. On the other hand, the hydraulic conductivity in coarse media tended to be more stable toward the addition of solids. Deeper straining allowed the solids to penetrate deeper in the filter bed and spread among the grains. As a result, the changes of head loss in filter columns with coarser media were insignificant. These results showed that the filter columns with finer media tended to experience faster clogging than the coarser media due to the faster formation of filter cake.

For the application in the real plant, a recommendation for the range of d_{10} values, which is divided into finer and coarser media, is allowed to be proposed based on the results of the study. A broader range of d_{10} values is introduced together with the risks that may occur due to the selection of the d_{10}. Table 23 summarizes the selection criteria between finer and coarser media.

Table 23. Selection criteria between finer and coarser media*

Criteria	Finer Media (d_{10} 0.25 – 0.50 mm)	Coarser Media (d_{10} 0.50 – 0.90 mm)
Average outlet turbidity	< 1 NTU	< 1 NTU, but higher than the finer media
Initial cost**	Higher	Lower
Dominant removal mechanism	Filter cake formation	Deeper straining
Filter run time	Shorter	Longer
Maintenance	Surface scraping or wet harrowing	Deeper scraping or replacement of the entire bed depth
Maintenance cost	Lower	Higher

*Based on the investigation under narrow graded media (C_u = 2.5)

**The cost to procure the sand

Investigation on the influence of different grain size distribution which varied in C_u was also conducted in two phases. In Phase I, it was found out that the removal efficiency of filter columns with narrow graded media, represented by C_u of 2.5 and 3, and wide graded media, represented by C_u of 5, was not significantly different. This finding where the filter columns with C_u of 5 produced high removal efficiency confirmed the previous results of Slezak and Sims (1984) and Di Bernardo and Escobar Rivera (1996).

Similar to the finding in the investigation of varied d_{10}, the range of recommended values for C_u by previous authors (Huisman and Wood (1974), Visscher (1990) and Barrett *et al.* (1991)) was also too limited. Therefore in Phase II, the range was extended and fine filter media with the C_u of 2.5, 3 and 7 were tested. The first two values of C_u represented the recommended values while C_u of 7 represented the extreme value. Based on the turbidity removal in Phase II, it was found out that filter column with C_u of 7 produced average outlet turbidity that around 42 % higher than the filter column with C_u of 2.5. However, the outlet turbidity values for all filter columns were lower than 1 NTU which indicated that the filtrate quality met the WHO turbidity standard. Related to the dominant removal mechanism, the statement from Huisman and Wood (1974) where the solids penetration might be deeper in the filter with higher C_u was not confirmed in this study. Formation of filter cake was observed in all filter columns independently from the C_u. This result indicated that the formation of filter cake was significantly influenced by the d_{10} and not by C_u.

In regard to the hydraulic conductivity, theoretically, the filter with higher C_u was expected to have lower initial hydraulic conductivity due to the reason that the finer fraction may occupy the larger pores and block the flow path (see **Error! Reference source not found.**). From this reason, it was also expected that the filter column with higher C_u would experience faster clogging period (Elisson, 2002; Langenbach, 2010). However, both predictions did not occur in this experiment. According to the measurement especially in Phase II, the values of initial hydraulic conductivity of the filter with wide graded media were higher than with narrow graded media. This discrepancy was as a result of the approach in the empirical values determination. The empirical calculation was mostly based on the grain size distribution of media neglecting the effect of the arrangement of grains and voids, the presence of air bubbles within the sand bed and the connections between void. With the addition of solids that retained in filter bed, the initial hydraulic conductivity of filter columns altered. Normally, the solids deposition, especially on the surface of filter bed forming filter cake, caused the decrease of hydraulic conductivity. This filter cake is a layer formed by the collection of very fine particles, therefore this layer inhibits the water flow. However, there was also a possibility where the hydraulic conductivity increased with the addition of solids especially when the filter cake is not yet formed. Increase of hydraulic conductivity in filter column could be caused by the alteration of grains and void arrangement and the release of entrapped air from the pores during the filter operation.

According to the observation in Phase II, the hydraulic conductivity of all filter columns decreased exponentially. The R^2 values of all models were very high ensuring the prediction of the influence of the solids addition on the relative hydraulic conductivity. A prediction on the relative hydraulic conductivity by taking a solids load value of 10,000 mg was done using the regression formula. It was found out that the relative hydraulic conductivity would be around 0.03, 0.10 and 0.13 for filter columns with C_u of 2.5, 3 and 7 respectively. Capacity of filter column with C_u 2.5 would only be 3 % of its initial after a load of 10,000 mg solids. Meanwhile, filter columns with higher C_u could still have around 10 % of its initial. This prediction indicated that the wider the grain size distribution of media, the longer the filter run would be. The results from this study approved the conclusion of Di Bernardo and Escobar Rivera (1996) who found out that lower C_u led to shorter filter run time. Based on the results in the investigation on the influence of C_u on the filter performance, a list of selection criteria is proposed in this study (see Table 24).

Table 24. Selection criteria between narrow and wide graded media*

Criteria	Narrow Graded Media (C_u < 3)	Wide Graded Media (C_u 5 - 7)
Average outlet turbidity	< 1 NTU	< 1 NTU, but higher than the narrow graded media
Initial cost**	Higher	Lower
Dominant removal mechanism	Filter cake formation	Filter cake formation
Filter run time	Shorter	Longer
Maintenance	Surface scraping or wet harrowing	Surface scraping or wet harrowing
Maintenance cost	Low	Low

*Based on the investigation under fine media (d_{10} = 0.26 mm)

**The cost to procure the sand

Actually, d_{10} and C_u are inseparable as both are the components which represent the grain size distribution of sand. Taking this into consideration, it is worth to discuss the overall results if the investigation on varied d_{10} and C_u. As it was mentioned in the previous section (see Section 2.7.1), d_{10} and C_u influence the hydraulic conductivity of filter media. By considering the results of the measurement (see Table 18 and Table 20), it could be inferred that the d_{10} influenced more the hydraulic conductivity than the C_u. As an example, filter column with d_{10} 0.075 mm/C_u 2.5 had an initial hydraulic conductivity which was two orders of magnitude lower than the filter column with d_{10} 0.70 mm/C_u 2.5. On the other hand, the initial hydraulic conductivity value of filter column with C_u 3/d_{10} 0.26 mm was similar to the value of filter column with C_u 7/d_{10} 0.26 mm. These results indicated that C_u did not influence the hydraulic conductivity values as significant as d_{10}.

Related to the removal mechanism, it could also be inferred that d_{10} had more significant influence than C_u at the beginning of filter operation. The lower the d_{10} was, the faster the filter cake was formed. In the filter columns with coarser media, formation of filter cake took longer time. Appendix 9 shows how the solids cover the entire area of filter column with finer media. Meanwhile, in the filter columns with coarser media, the filter cake layer was not yet formed evenly on the entire bed surface. The faster the filter cake formation was, the faster the filter operation had to be terminated due to the significant decrease of hydraulic conductivity and increase of head loss. By considering that filter cake was formed in filter columns NG-1.1, NG-2.1 and WG-2 independently from the C_u, it could be inferred that the C_u did not influence the dominant removal mechanism as significant as the d_{10}. However, the influence of d_{10} was only significant at the beginning of filter operation. Once the filter cake is formed, the removal efficiency and the changes in the filter capacity are dependent on this layer which acts as the secondary filter.

From the experiment of high hydraulic loading rate in Phase I, it was not expected that filter performance was better under 0.60±0.15 m/h. This phenomenon could be explained due to the existence of suspended solids within the filter bed. When the high hydraulic loading rate was applied to the filter columns, 22,500 mg of suspended solids had been loaded and retained in the filter bed. Based on the observation, these solids mostly accumulated on the surface of filter bed. They might act as another strainer for the artificial raw water therefore enhancing the filter performance.

In Phase II, the performance of filter columns operated under different hydraulic loading rates could be compared precisely. From the perspective of solids removal, the recommendation was to apply a low hydraulic loading rate in order to ensure the removal efficiency (Huisman and Wood, 1974; Visscher, 1990; Barrett *et al.*, 1991). However, the range of the recommended hydraulic loading rate given by those previous authors was rather narrow. Meanwhile based on the results of previous tests, especially on the high rate experiment in Phase I, it could be inferred that once the filter cake is formed, the removal efficiency is no longer dependent on the on the hydraulic loading rate as proven by the better effluent quality.

Operated at a hydraulic loading rate of 0.8±0.2 m/h filter column High-1 performed lower than the filter column Low-2 which was operated at 0.20±0.05 m/h. The average outlet turbidity of filter column High-1 was only two and a half times higher than the filter column Low-2 even though the hydraulic loading rate was four times higher. Moreover, the average value was still in the standard value of WHO i.e. below 1 NTU. From this result, it could be inferred that the removal efficiency of filter column with fine media operated at a high hydraulic loading rate did not deteriorate significantly.

According to the analysis of suspended solids penetration, filter cake was formed in all filter columns. However, from the values in Figure 59, it could be inferred that in the higher the hydraulic loading rate was the longer time needed for the filter cake to be formed. Solids penetrated deeper in the media of filter column High-1. On the contrary, in the filter columns operated at lower hydraulic loading rate, the filter cake formed faster. As a consequence, the hydraulic conductivity of filter column Low-1 and Low-2 decreased greater than the filter column High-1. Gradual increase on head loss could also be observed in all filter columns due to the decrease of hydraulic conductivity. The regression analysis of relative hydraulic conductivity also showed that filter columns operated at lower rate tended to clog faster than the one operated at higher rate.

A recommendation on the method for increasing the hydraulic loading rate can be proposed based on the results of the investigation on the different rates. First, it is recommended to use fine and narrow graded media if the filter is planned to be operated at high hydraulic loading rate from the beginning of the operation. Second recommendation is to increase the hydraulic loading rate after the ripening period is passed.

Taking into consideration the results of Phase I and Phase II in regard to the suspended solids removal, a new recommendation for the range values of design criteria especially for d_{10}, C_u and hydraulic loading rate is proposed and listed in Table 25. By applying higher hydraulic loading rate, the filter area can be reduced significantly. Hydraulic loading rate of 0.60 m/h is preferably than 0.80 m/h based on two considerations. The first is that the filter column operated under 0.60 m/h performed better in regard to the turbidity removal. The second consideration is related to the solids penetration in the filter bed. Hydraulic loading rate of 0.80 m/h contributes to the deeper penetration of solids in filter bed which will lead into either higher possibility of breakthrough or higher cost during the filter maintenance.

It is not recommended to use coarse sand with high C_u because in such configuration the arrangement of grains and pores is heterogeneously distributed. Therefore, it will be difficult to control an even hydraulic loading rate. Moreover, the stability of the filter bed may be very poor because the risk of washout of finer media is high. It is also worth to noting that this new recommendation is addressed for the purpose of water quality improvement before disinfection process.

Table 25. Comparison of the past and new recommendation values of the design criteria of slow sand filtration

Design Criteria	Recommended Values	
	1. Huisman and Wood (1974) 2. Visscher (1990) 3. Barrett et al. (1991)	Anggraini (2017)
Hydraulic loading rate in the filters	1. 0.1-0.4 m/h 2. 0.1-0.2 m/h 3. 0.04-0.4 m/h	0.20-0.60 m/h*; > 0.60 m/h up to 0.80 m/h can be alternatives for fine media e.g. d_{10} ±0.25 mm/C_u < 3
Sand specification:		
Effective size d_{10}	1. 0.15 – 0.35 mm 2. 0.15 – 0.30 mm 3. 0.20 – 0.30 mm	0.25 – 0.50 mm; 0.50 – 0.90 mm can be alternatives as long as the filter will be operated at ≤ 0.40 m/h
Uniformity coefficient (C_u)	1. < 3, preferably < 2 2. < 5, preferably < 3 3. 1.5 – 2, > 3 for economic reasons is considerable	2.5 – 7 for d_{10} < 0.50 mm; < 3 is preferable for d_{10} > 0.50 mm

As part of the research, the method of prolonging the filter run by applying protection layer (Mälzer and Gimbel, 2006) was evaluated. In this study, the development of head loss and the observation on the solids penetration proved that adding gravel as a protection layer for the filter bed was an effective method to prolong the filter run time. In regard to the removal of suspended solids, performance of both filter columns, with and without protection layer, was satisfactorily. The average values of outlet turbidity from both filter columns met the requirement of WHO. This result confirmed the previous test in the Pre-Experiment Phase which figured out that the removal efficiency of filter columns with and without protection layer was similar.

After the filter operation was terminated, it was found out the hydraulic conductivity of filter column with protection layer was decreased insignificantly compared to the filter column without protection layer. The decrease of hydraulic conductivity in the filter column without protection layer was around three times greater than the decrease in the filter column with protection layer. In the filter column without protection layer, the solids were retained directly on the surface of filter bed. The constriction size of sand bed was certainly lower than of gravel layer. Hence, as proven by the observation in the solids penetration (see Figure 64), the formation of the secondary filter layer in the filter column without protection layer was faster than in the filter column with protection layer.

Behavior of filter column toward the addition of solids could also be observed from the development of head loss. The gradual increase of normalized head loss at 0.20 m/h in the filter column without protection layer was found out to be significant. It indicated that the filter column without protection layer tended to clog faster than the filter column with protection layer. The difference of the final and the initial normalized head loss at 0.20 m/h in the filter column without protection layer was around 28 cm. In the contrary, the increase of normalized head loss at 0.20 m/h in the filter column with protection layer was only around 2 cm.

Those results above indicated that the presence of protection layer may inhibit the occurrence of clogging. Therefore, the recommendation of Mälzer and Gimbel (2006) to add the protection layer so that the filter run time can be prolonged is an appropriate method.

6.2 Case Study – Slow Sand Filter in Gunungkidul, Java Indonesia

The district of Gunungkidul is one of the poorest regions in Java Island, Indonesia which suffers from severe water scarcity especially during the dry season (April – October). Due to its karst topography, the water percolates rapidly to the underground forming subsurface rivers. In general, local population may derive their water supply from wells, surface water, rainwater harvesting and piped water from the public utility PDAM (Nestmann *et al.*, 2009). However, there are some limitations from these water sources i.e. most wells and surface water run dry during the dry season, the cost to construct the rainwater storage tanks is not easily affordable for most of the local population and the level of service of the pipe water is very poor (Fuchs *et al.*, 2015).

By considering those conditions, an Integrated Water Resources Management Indonesia Project (IWRM Indonesia) was established in Gunungkidul. Within the framework of the project, an additional water intake was developed by constructing an underground dam with an integrated micro-hydro power plant to pump out the water from Bribin cave to a reservoir built in Kaligoro. This reservoir supplies the water for 3.5 % of the total population which are served in the water supply system (Fuchs *et al.*, 2015). In regard to the quality, the water does not meet the requirements of any regulatory standard of drinking water (Silva, 2010; Anggraini, 2011). Hence, a water treatment is needed to improve the water quality. As part of the project, a pilot plant of slow sand filter was installed in Kaligoro to improve the water quality by removing suspended solids.

Based on Fuchs *et al.* (2015), the pilot plant was designed to treat an amount of 195 m^3 per day which can be used to serve five sub-villages (around 2,800 inhabitants). By considering the recommended values of design criteria (Table 1), Fuchs *et al.* determined the hydraulic loading rate for the plant was 4 m/d (≈ 0.20 m/h). In order to encompass these criteria, the total filter bed are of 50 m^2 was needed. This filter area was divided into two filter beds with 25 m^2 each. To maintain the continuous supply during the clogging and maintenance period, four additional filter beds were needed. In total, six filter beds with an area of 25 m^2 each were proposed. Table 26 presents the proposed design criteria for the plant in Kaligoro. However, the local authorities agreed to construct only half of the proposed plant due to the budget procurement. Therefore, the amount of sub-villages that should be supplied was also reduced by around the half. Figure 65 shows the layout of the filter unit.

Table 26. Proposed design criteria for slow sand filter plant in Kaligoro (Fuchs *et al.*, 2015)

Design Criteria	Value
Filter bed area	25 m^2 per unit
	Total 6 filter units
Hydraulic loading rate	4 m/d (≈ 0.20 m/h)
Height of filter bed	
Initial	0.8 m
Minimum	0.5 m
Specification of sand	Lava sand
Effective size d_{10}	0.25 mm
Uniformity coefficient C_u	3.06
Height of underdrain including gravel layer	0.25 m
Height of supernatant level	1 m

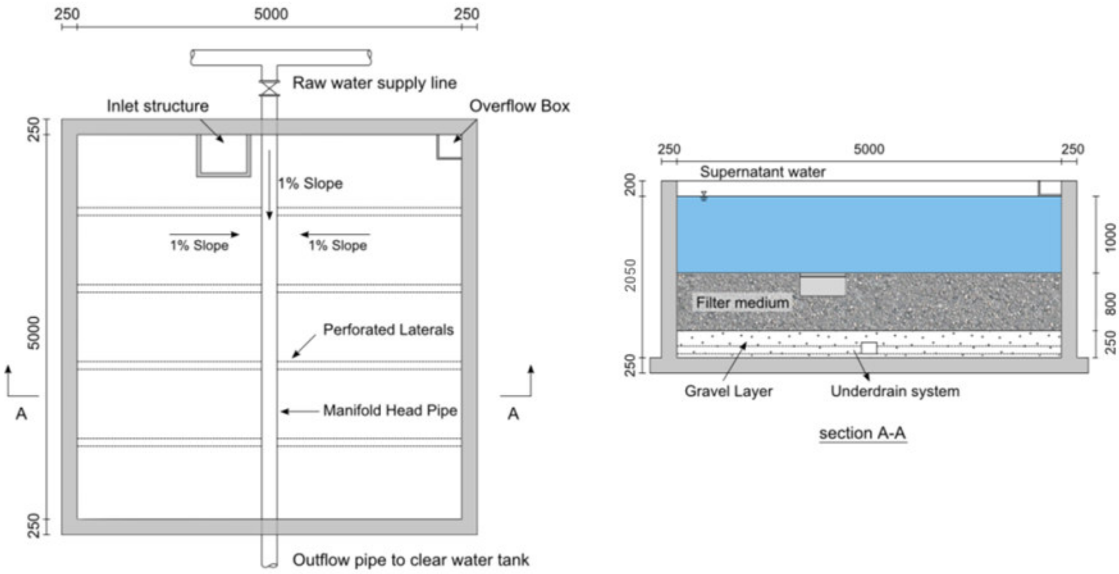


Figure 65. Layout of the slow sand filter in Kaligoro (*drawn not to scale*: IWRM-Indonesia (2015))

The construction works of the pilot plant was started in July 2013 (see Figure 66). During the monitoring period in August 2014, it was found out that the filter media loaded to the chambers were not in accordance with the proposed design. According to the sieving analysis that was conducted at the Soil Mechanics Laboratory, Department of Civil and Environmental Engineering, Gadjah Mada University, the filter media contained 34.26 % gravel (see Appendix 11). Therefore, the filter media was sieved to separate the gravel from the sand fraction. At the end the d_{10} of the media was 0.30 mm and the C_u was 2.93 (Nugraha, 2016).

Figure 66. Construction works in Kaligoro (Fuchs *et al.*, 2015)

Performance of slow sand filter plant had been monitored in 2015 for one month period (Nugraha, 2016). As a part of the monitoring, the turbidity of inlet and outlet was measured. The comparison of inlet and outlet turbidity is presented in Figure 67. Average turbidity removal was 43 % and the outlet values were all below the national turbidity standard of Indonesia i.e. 5 NTU. However, it is worth noting that the measurement was done during the ripening period when the dirt layer (*Schmutzdecke*) had not developed yet. It could be estimated that after the *Schmutzdecke* has been developed, the outlet turbidity can be lower than the values at the ripening period. Due to these low values of outlet turbidity, it could be inferred that the next treatment step i.e. disinfection can be performed effectively.

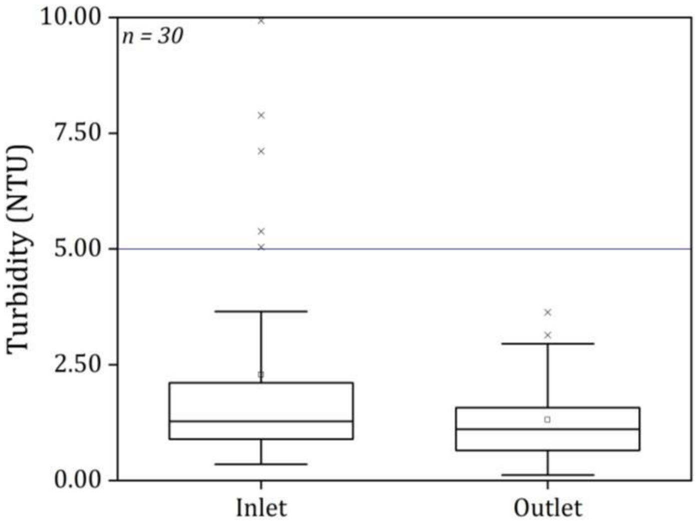


Figure 67. Inlet and outlet turbidity of slow sand filter in Kaligoro after Nugraha (2016)

At the moment, this plant was not in operation and abandoned (see Figure 68). It was found out during the last monitoring of implemented plant, which was done in July 2017, that due to the low capacity of the plant, the local water company PDAM which should be responsible of the plant operation decided not to use it.

Figure 68. Current condition of slow sand filter in Kaligoro (*Doc.: Marjianto, 2017*)

With regard to its function and performance on improving the water quality, it is worth to put this plant into operation. However, due to the current condition of the plant and the issue regarding the plant capacity, some improvements on the constructed plant have to be made. Based on the results of this research, the following are some recommendations in regard to the filter media, the hydraulic loading rate and the construction that can be proposed (see also Table 27):

1. *Filter Media*

   According to Figure 68, some plants grow in the chambers of the plant. The risk that some parts of the plants are decomposed in situ is very high. These decaying materials may deteriorate the filtrate quality. Therefore, it is recommended to replace the entire filter media in the three chambers. In regard to the sand specification, the d_{10} does not necessarily to be very fine and the C_u does not necessarily to be as narrow as the previous recommended values by Huisman and Wood (1974), Visscher (1990) and Barrett *et al.* (1991). In order to ensure the filter performance and by considering the peak turbidity during the rainy season, a d_{10} of 0.25 - 0.50 mm and C_u of 3-7 can be selected. The d_{10} values of 0.70 mm and 0.90 mm were not recommended because the solids may penetrate very deep into the filter bed and led to higher maintenance cost because surface scraping will not be sufficient. By having a coarser and ungraded media the capital cost may be reduced because further sieving process does not need to be done. Lava sand can still be chosen because this material is abundant locally.

2. *Hydraulic Loading Rate*

   Based on the results of the study, higher hydraulic loading rate may reduce the removal efficiency. However, it was also found that a hydraulic loading rate of 0.8±0.2 m/h could still reach an average outlet turbidity of below 1 NTU. In the case of slow sand filter Kaligoro, the low capacity can be increased by raising the hydraulic loading rate so that the five sub-villages can be supplied with improved water. In order to achieve this purpose, the hydraulic loading rate only needs to be increased two times of the original proposal i.e. 8 m/d (≈ 0.40 m/h). Since the higher hydraulic loading rate (0.8±0.2 m/h) was capable to achieve high removal efficiency, it can be ensured that higher performance can be obtained by operating the filter at lower hydraulic loading rate (0.40 m/h).

Table 27. Comparison of previous and current proposed design criteria for slow sand filter Kaligoro

Design Criteria	Previous Value	Current Value
Filter bed area	25 m² per unit	25 m² per unit
	Total 6 filter units	**Total 3 filter units**
Hydraulic loading rate	**4 m/d (≈ 0.20 m/h)**	**8 m/d (≈ 0.40 m/h)**
Height of filter bed		
Initial	0.8 m	0.8 m
Minimum	0.5 m	0.5 m
Specification of sand	Lava sand	Lava sand
Effective size d_{10}	**0.25 mm**	**0.25 – 0.50 mm**
Uniformity coefficient C_u	**3.06**	**2.5 - 7**
Height of underdrain including gravel layer	0.25 m	0.25 m
Height of supernatant level	1 m	1 m

3. *Construction of Filter Plant – Outlet Position*

The outlet position of current plant is located at the bottom of the chamber (see Figure 69). The outlet pipe is directly connected to the clean water storage tank which is placed next to the filter and below the base of the filter chambers. In this position, the Δh is too high and leads to the difficulty of controlling the water flow at the desired rate. To ensure the filter is operated at the desired rate and to have a better control of the rate, it is recommended to reduce the Δh. The approach is to adjust the point where the water comes in to the storage tank up to the level around the surface of sand bed. Therefore, the storage tank has to be put at least 1,000 mm higher than the current level (see Figure 70).

Figure 69. Outlet position of current filter plant in Kaligoro

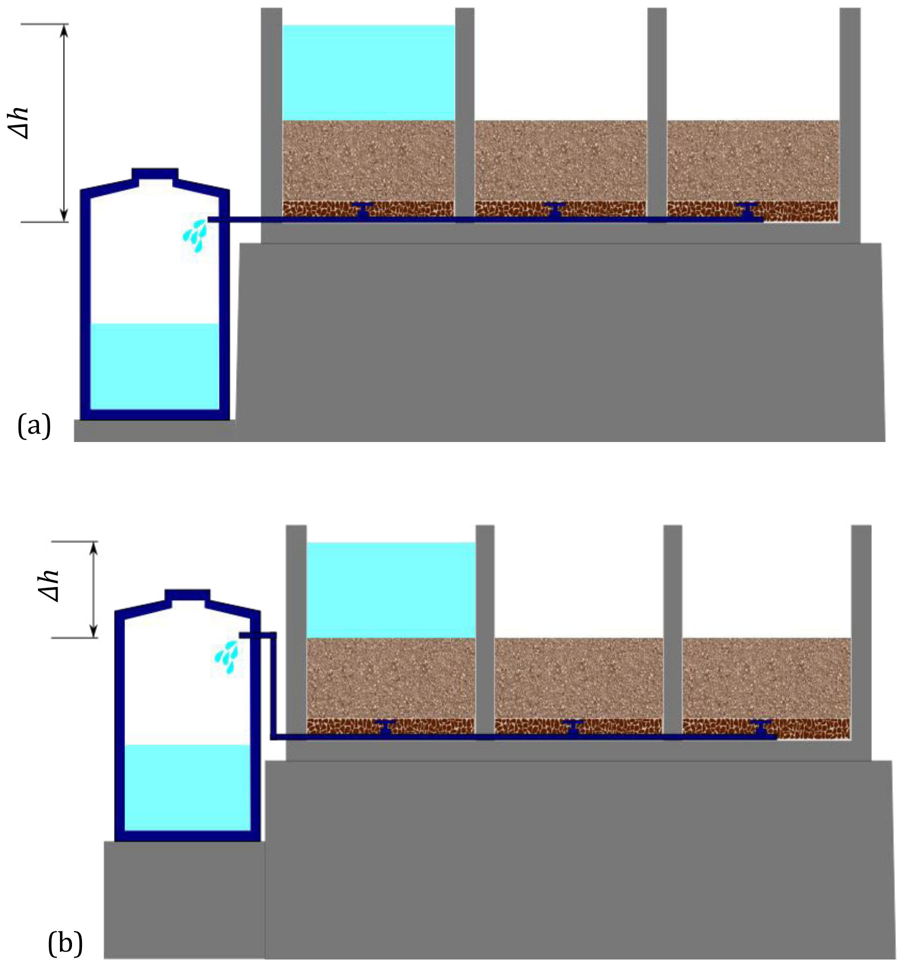


Figure 70. Sketch of current (a) and recommended (b) outlet position of slow sand filter in Kaligoro (not *drawn to scale*)

7 Conclusion

Based on the results of this research, some conclusions can be drawn as follows:

1. The current range values that were recommended in the design criteria of slow sand filter was rather conservative. As a consequence of this limited range, the optimization and the improvement of the technology were also limited. It was proved that coarser filter media represented by d_{10} 0.90 mm/C_u 2.5, which was almost three times greater than the upper limit of the current recommended values, could produce low value of outlet turbidity i.e. below 1 NTU averagely. Under this average value, the disinfection process could be performed effectively. It was also found that for the filter with fine media, the hydraulic loading rate could be increased up to 0.80 m/h which was two times the upper limit of the current recommended values. By operating the filter at 0.80 m/h, the average outlet turbidity was also found to be below 1 NTU. As a result of a higher hydraulic loading rate is that the area needed for the construction of slow sand filter could be reduced significantly. Therefore, the design criteria can be optimized by considering these results (see Table 27). Nevertheless, this new recommendation on the range values of the slow sand filtration design criteria have to be tested for the biological removal and further in a larger scale to provide a more comprehensive findings.

2. In this study, it was figured out that the operating variables did not significantly influence the removal efficiency. However, the operating variables, especially the d_{10} of the grain size distribution, influence significantly the period needed for the dirt layer to be formed. It was found out that the finer the media, the faster the formation of dirt layer on the surface of filter bed is. The faster the formation of the dirt layer is, the faster the filter will experience clogging period. This clogging period can be identified by the significant decrease of hydraulic conductivity and increase of head loss. As an example, by comparing the d_{10} of 0.26 mm/C_u 2.5 and d_{10} 0.50 mm/C_u 2.5, it was identified that the clogging in the finer filter column would occur for two and a half time faster than the coarser filter column.

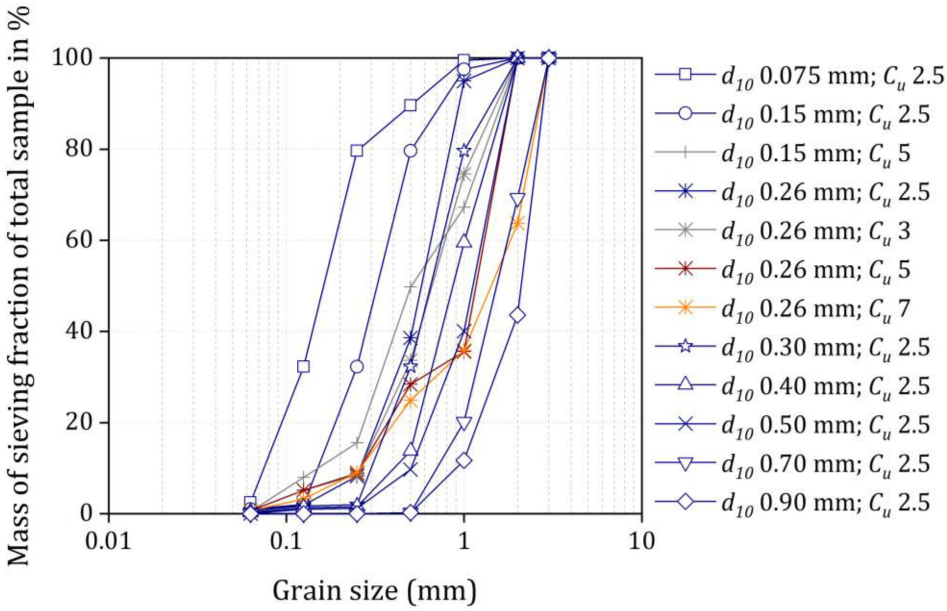
3. A method to enhance the hydraulic loading rate can be proposed by taking into consideration the formation of dirt layer. It was found out that after the dirt layer is formed, hydraulic loading rate was no longer affecting the filter performance. In this case it has been proved in this study that once the dirt layer has been formed, the hydraulic loading rate can be enhanced up to three times without deteriorating the filter performance.

4. Applying protection layer in the filter can be a promising method to increase the filter run time. It was proved that by adding gravel as a protection layer, the decrease of filter capacity of the filter could be 70 % lower than the decrease of filter without any protection layer.

5. The implementation of a technology, especially in the developing countries, should consider many aspects such as the socio-economic condition, human resource, local policy etc. Another important factor is to develop the sense of belonging of the technology among the local people so that the technology can last in a long term. This sense of belonging can be grown by implementing an appropriate technology. Implementation of too advanced technology in rural areas in developing countries may be redoubtable for some local people in which they do not want to deal with it. Slow sand filter can be a promising technology which is appropriate for the people living in developing countries especially in rural areas. Its simplicity in the construction, operation and maintenance process does not require the skilled personal. Further, education on the personnel in charge so that they can have an advanced skill will also support the successful implementation of the technology.

Appendix

Appendix 1. Grain size distribution of filter media for systematic investigation

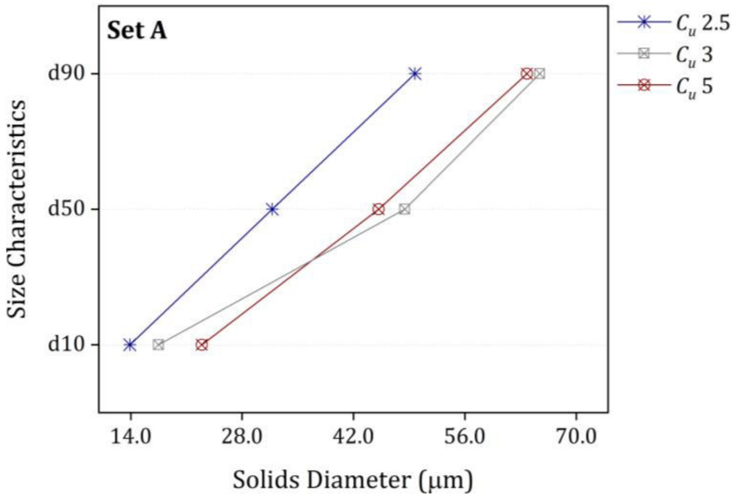


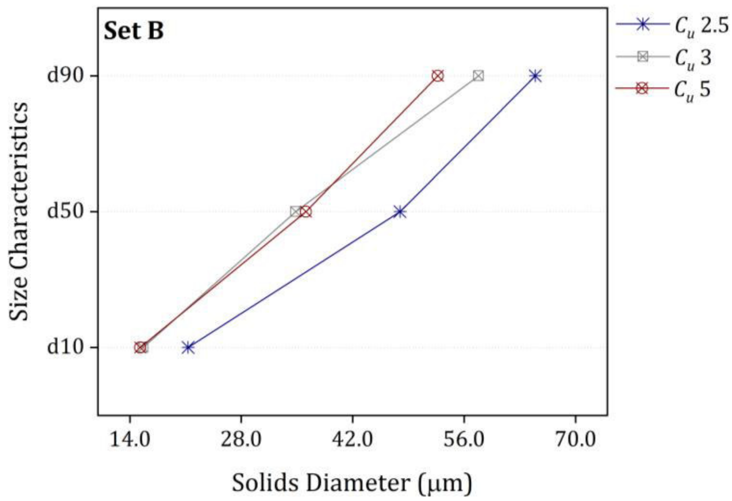
Appendix 2. Specific surface area of filter columns in all tests

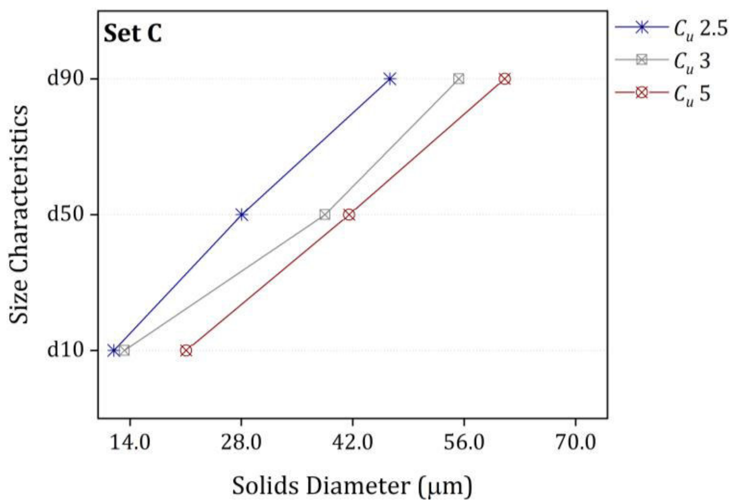
Specific surface area does not have any influence on the suspended solids removal but it will have a big influence on the bacteria removal as has been studied by Orb (2012)

Phase	Filter Columns	Specific Surface Area A_s (m^2/m^3)		
		Set 1	*Set 2*	
	Fine-1	25,987		
	Fine-2	14,699	13,224	
	Fine-3	8,243	8,628	
	Coarse-1	5,583	5,467	
Phase I	Coarse-2	4,423	4,535	
		Set A	*Set B*	*Set C*
	NG-1	8,759	8,760	8,758
	NG-2	8,050	8,050	8,077
	WG-1	6,587	6,680	6,799
	Fine-1.1	29,960		
	Fine-3.1	8,376		
	Coarse-2.1	4,441		
	Coarse-3	3,060		
	Coarse-4	2,413		
	NG-1.1	8,115		
Phase II	NG-2.1	7,913		
	WG-2	5,892		
	Low-1	8,623		
	Low-2	8,115		
	High-1	8,428		
	NG-1.1PL	8,474		

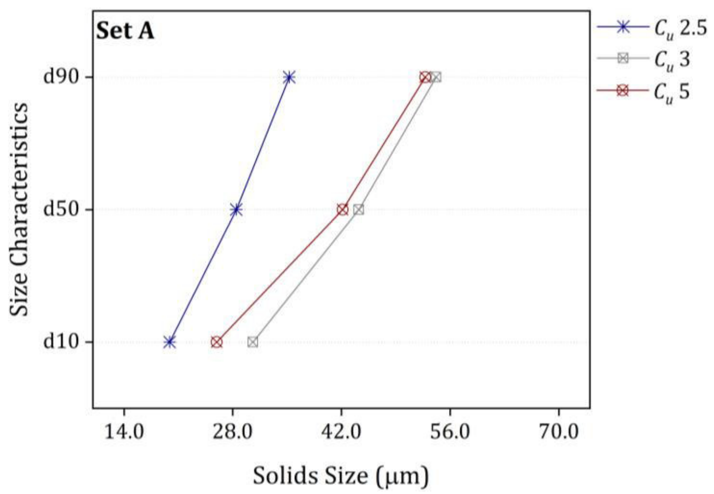
Appendix 3. Solids size distribution in the outlet of filter columns in Phase I-varied C_u

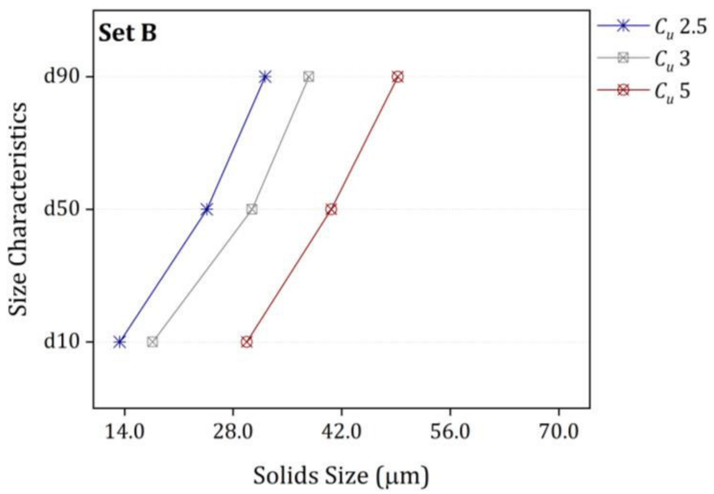


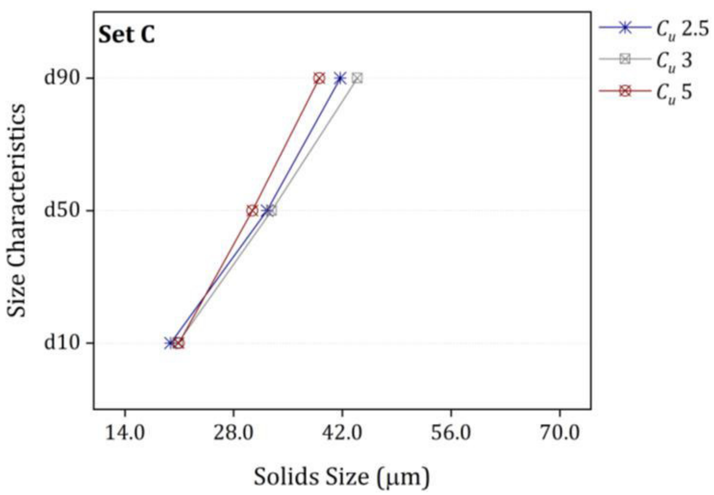




Appendix 4. Solids size distribution in the outlet of filter columns in Phase I-high hydraulic loading rate (0.60±0.15 m/h)



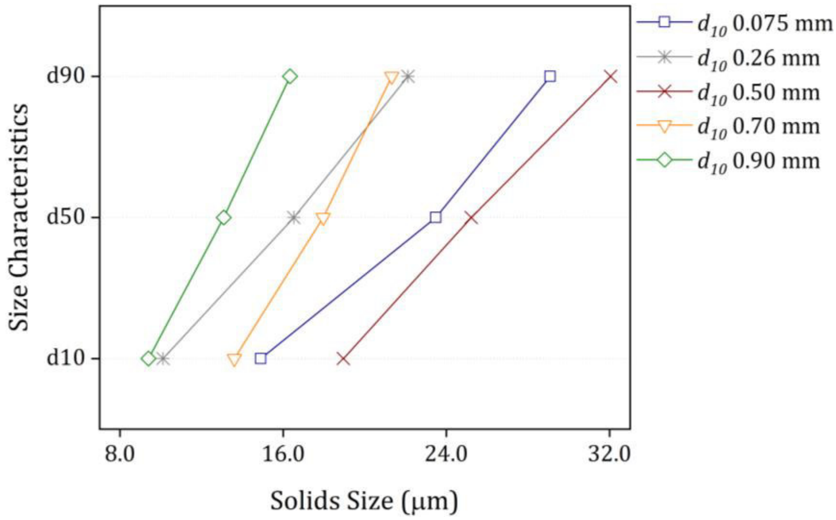




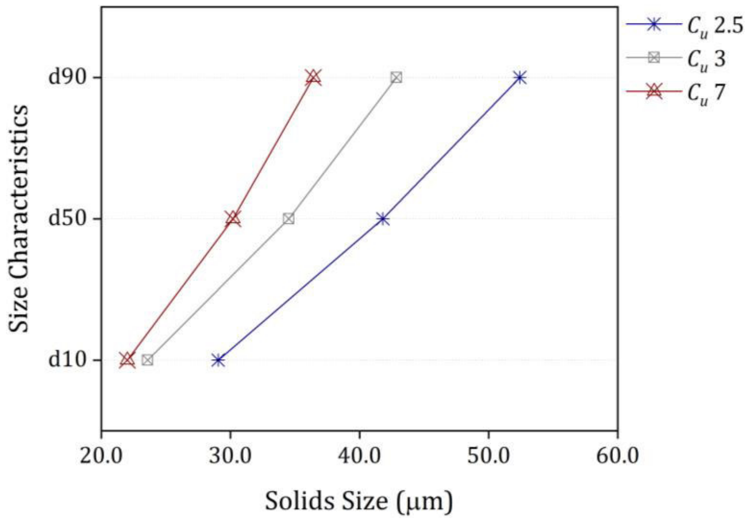
Appendix 5. Filter columns in Phase II

Appendix 6. Process of sand samples shaking during the analysis of solids penetration in Phase II

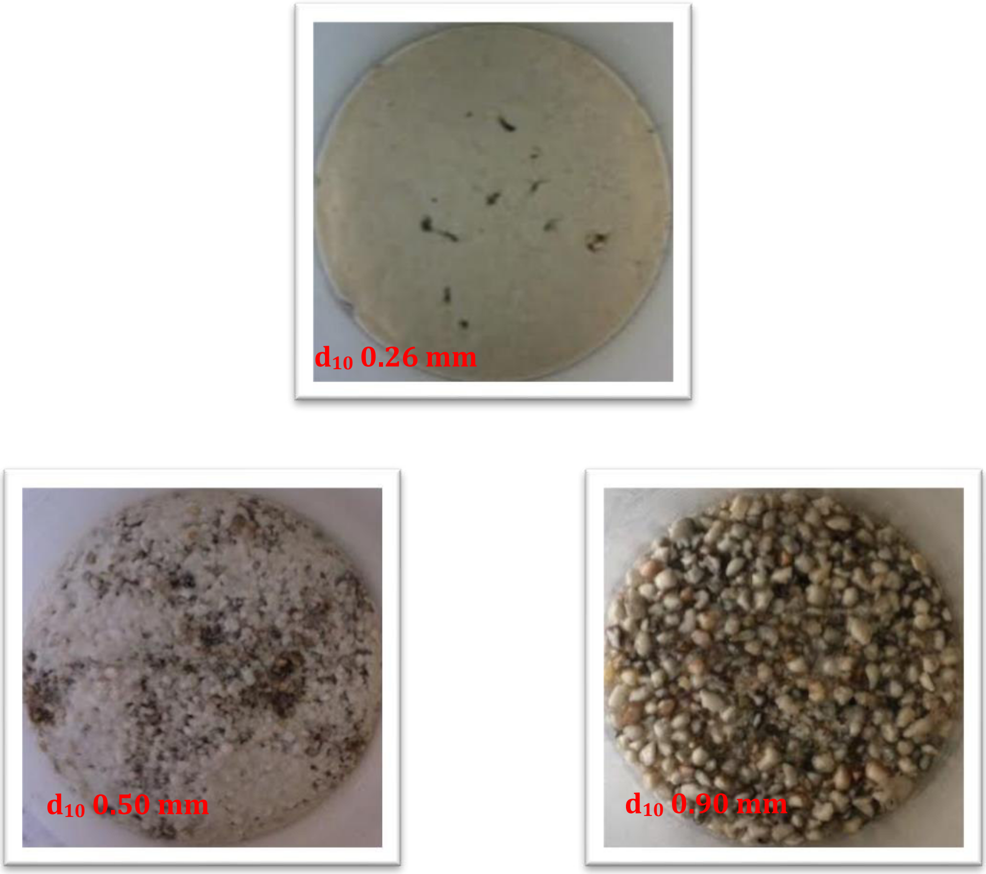
Appendix 7. Solids size distribution at the outlet of filter columns in Phase II-varied d_{10}



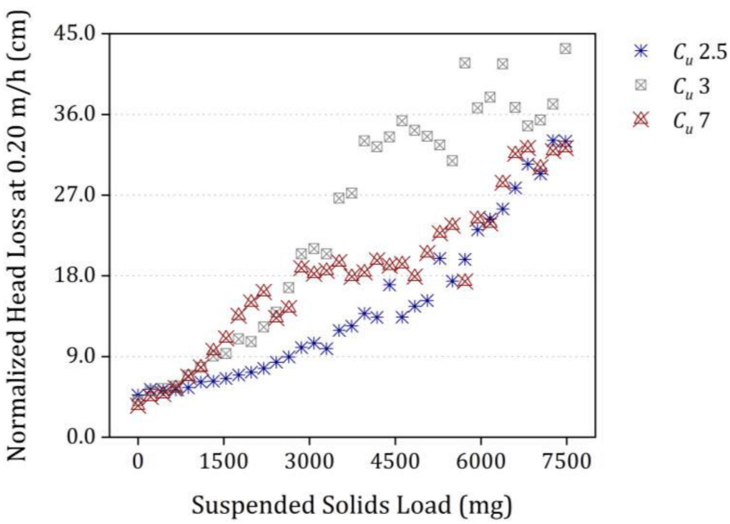
Appendix 8. Solids size distribution at the outlet of filter columns in Phase II-varied C_u



Appendix 9. Formation of filter cake in Phase II - test of varied d_{10}



Appendix 10. Development of normalized head loss at 0.20 m/h in the Phase II-varied C_u



Appendix 11. Grain size analysis of filter media of slow sand filter Kaligoro before sand-gravel separation

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FAKULTAS TEKNIK - JURUSAN TEKNIK SIPIL & LINGKUNGAN
LABORATORIUM MEKANIKA TANAH - GEOTEKNIK

GRAIN SIZE ANALYSIS

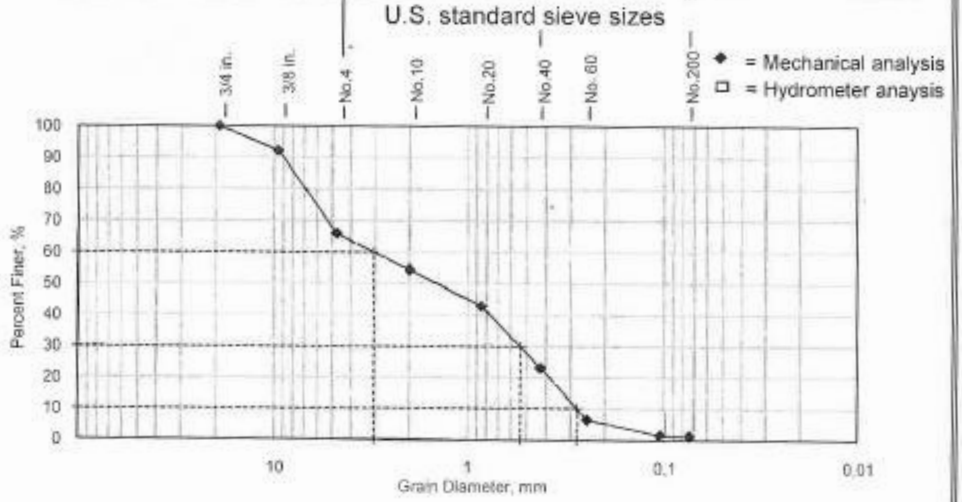
Project : SSF Kaligoro dan Pasir
Location : Media Filter SSF Kaligoro
No. : I

Depth : -
Date : 11 Agustus 2014
Made by : Ris

Specific Gravity ________

Description of soil ________

Gravel	Sand		Fines
	Coarse to medium	Fine	



Finer # 200 = 1,32 %

Gravel = 34,26 %
Sand = 64,43 %
Silt/Clay = 1,32 %

D_{10}	D_{30}	D_{60}	$C_u = D_{60}/D_{10}$	$C_c = (D_{30})^2/(D_{10} \times D_{60})$
0,278	0,540	3,064	11,02	0,34

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