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Detention Properties of Subsurface Stormwater Modules Under Tropical Climate

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Abstract: Subsurface stormwater module is one of the components of a sustainable drainage system. However, the performance of subsurface stormwater module as on-site detention under tropical climate like Malaysia has not been extensively studied in the literature. The current study involves on-site installation of pilot scale subsurface stormwater modules exposed to tropical climate to simulate real conditions to evaluate the detention performance. Rainfall together with the changes in water level and volume of water detained in the installation were observed for six months between April 2021 to October 2021. The subsurface stormwater module used in the current study has a porosity of 94%. It was found that the subsurface stormwater module setup was able to detain between 35.2% to 95.6% of the rainfall volume generated from total rainfall between 11.1 mm to 56.8 mm. The findings can be used as design consideration for using subsurface stormwater module under tropical climate.

Keywords: Flash flood, on-site detention, stormwater management, sustainable drainage, urban

1. Introduction

Rapid development in urban areas alter the natural balance between runoff and natural absorption areas by replacing natural areas with greater amounts of impervious surface. This necessitates the development of new sustainable stormwater management strategies that can promote infiltration and reuse, quality enhancement and quantity reduction [1]. Stormwater modules have been applied as part of sustainable drainage and rainwater harvesting system. Stormwater modules are generally made of plastic material and placed underground to collect water, act as temporary pond before discharging the water into drainage system, thereby inhibits flooding due to excessive stormwater runoff. Stormwater modules are designed in different shape and patterns to increase lag time in the flow (attenuation), reduce the flow volume by enhancing groundwater recharge and provide storage [1]. The use of subsurface stormwater modules has been recommended in the Urban Stormwater Management Manual for Malaysia, 2nd Edition [2] if there is insufficient space for a swale, where the flow can be divided into surface and subsurface conduits. The subsurface stormwater modules can also trap water at the source where it can be retained in the modules. Hence, subsurface stormwater modules can be used to temporarily store floods (detention) or to convey flow (drainage).

The effectiveness of subsurface stormwater modules as storage system has been evaluated by Mohd Sidek et al. [3] where three different storage systems namely modules storage tank (without infiltration to surrounding soil), loose rock infiltration system and modules infiltration system have been compared. It was found that in terms of peak flow

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attenuation, the system with the modules infiltration system performs better than the other two systems with the highest percentage of peak flow reduction at the outlet of the storage system. In terms of volume attenuation, again, modules with infiltration system performed better than the other two systems with 27% as compared to 19% for loose rock infiltration system and 3.45% for modules storage tank system for 2-year storm [3]. As comparison, a more recent study using modular pre-cast concrete stormwater detention system has shown the effectiveness to detain between 30% to 74% of runoff for total rainfall depth of 42.5 mm to 117.5 mm [4]. One of the factors that determine the water volume that can be detain by the stormwater modules is the porosity/cavity/void ratio of the modules. Existing literature has quoted high porosity value such as 0.75 (75%) [5], 0.82 (82%) [6] and 0.85 (85%) for the existing stormwater modules [7].

As for flow conveyance purpose of the subsurface stormwater modules, Kee et al. [6] suggested lower roughness for design of conveyance system as compared to usage as modular tank. This is to prevent problem such as localize water ponding. Using their modular plate design for slope between 0.001 to 0.002, Kee et al. [6] found that the Manning roughness coefficient varies between 0.012 to 0.020. Work by Mohammadpour et al. [7] has found that the Manning's roughness coefficient was affected by the Froude number of the flow, the slope of the channel, the total modules porosity, number of modules per meter and flow depth to width ratio.

The current study was conducted to evaluate the suitability of a new stormwater module design to be used under local condition. The current study consists of on-site setup of the stormwater modules to simulate real conditions similar to the common practice of subsurface stormwater modules construction. The objectives of the current study were to determine the volume and void ratio as well as the detention capacity of the new stormwater modules under on-site rain condition.

2. Methodology

The current study was conducted using a new stormwater modules design with the commercial name MOVA stormwater module. The study can be divided into two stages namely, (i) Determination of the stormwater modules volume and void ratio; and (ii) Setting up and monitoring of on-site stormwater modules in terms of detention capacity.

2.1 Determination of Stormwater Module Volume and Void Ratio

The dimensions for a single stormwater module unit used in the current study were measured. The measurement was done not only on the length, width and depth, but also for every line and thickness of the stormwater module structure. The stormwater module used was of dimensions 0.5 m (W) x 0.5 m (D) x 0.5 m (L) as shown in Fig. 1. From the measurement, the net volume (NV) and porosity (P) of every single unit can be calculated using Eq. (1) and Eq. (2):

$$NV = TVWS - TVS \tag{1}$$

$$P = \frac{NV}{TVWS} \times 100\% \tag{2}$$

where NV is the Net Volume (m^3), TVWS (m^3) is the total volume without structure (0.5 m x 0.5 m x 0.5 m) and TVS (m^3) is the total volume of structure which is the spaces occupy by all the lines of the design of the stormwater module. To obtain TVS, all the design lines were measured for the length, width and thickness to obtain the volume.

A graph of the water level with the occupied volume can be plotted for a single unit of the stormwater module. From the calculation of the single unit, the graph for the water level and the occupied volume for the on-site setup can be obtained by multiplying with the total number of the stormwater module unit used.

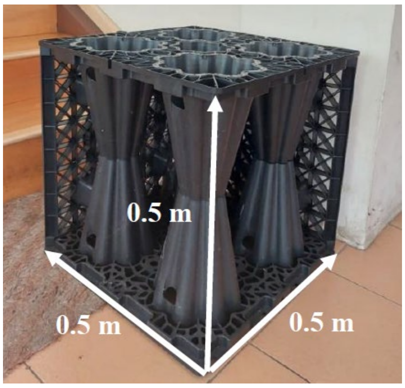

Fig. 1 - General dimension for a single unit of stormwater module used in the current study

2.2 Setting Up and Monitoring of On-Site Stormwater Modules

To study the effectiveness of the stormwater modules detention properties under different rainfall depth, an installation of the stormwater modules as subsurface stormwater tank was set up on-site. The schematic diagram of the setup was as shown in Fig. 2. In Fig. 2, upper part of the setup (label 'A') was made up of top soil (0.2 m thick) and gravel (0.10 m thick) while the lower portion (label 'B') was made up of the stormwater modules (0.5 m thick). The setup was approximately 5.0 m (L) x 2.0 m (W) x 1.10 m (D) as shown in Fig. 3.

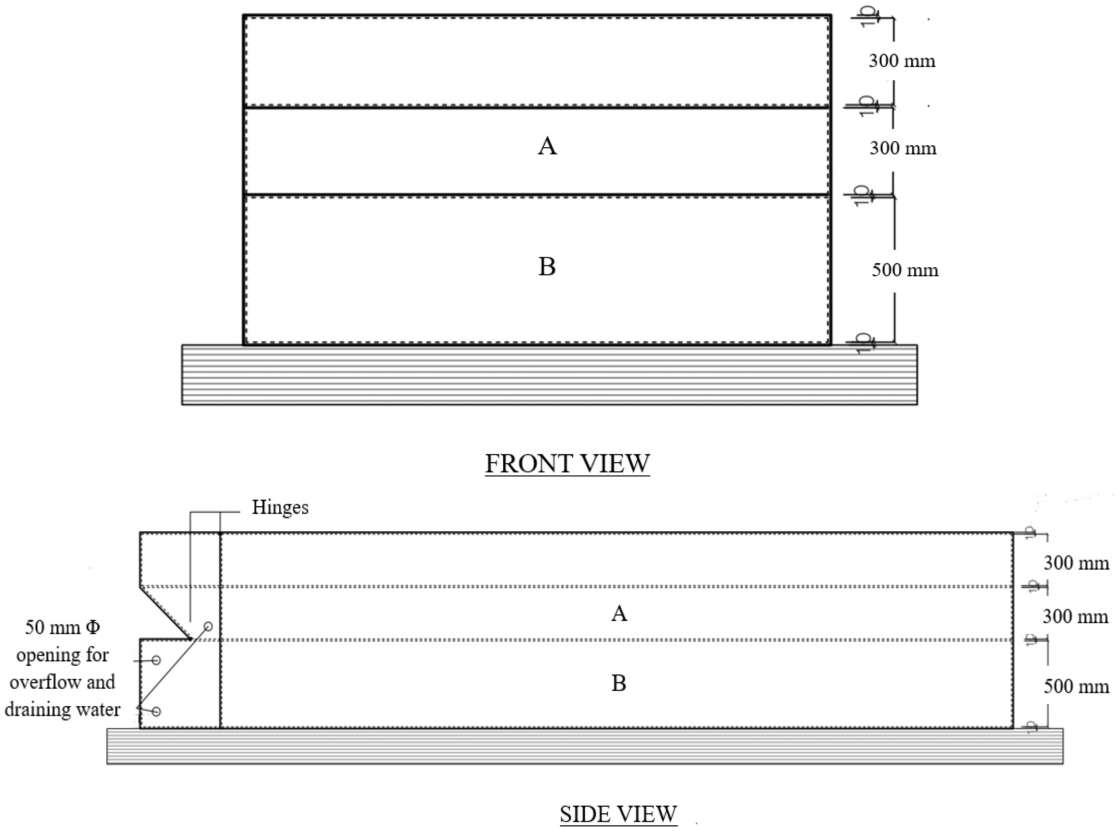

Fig. 2 - On-site setup for the stormwater modules

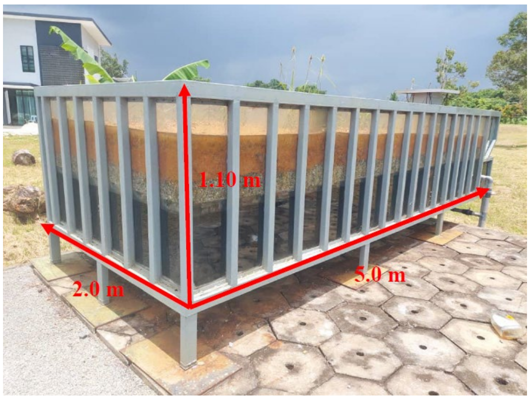

Fig. 3 - Rear view and dimensions of the on-site setup

A tipping bucket rain gauge was installed on the site about 100 m from the stormwater modules setup to record the rainfall during the observation period. Water level sensors were also installed in the stormwater modules setup to record water level inside the modules. Daily rainfall and daily water level data were collected. From these data, the total volume of water generated from the rainfall can be calculated using Eq. (3).

$$\sum V_R = d_R \times A_s \tag{3}$$

where ΣV_R is the total water volume from rainfall (m^3), d_R is the rainfall depth (m) and A_s is the area of setup (m^2).

The area of setup is the surface area which is 5 m (L) x 2 m (W) as shown in Fig. 3. To allow time for the infiltration, the water level was observed daily until no changes was observed. The water level difference will be calculated by deducting the final water level with the water level prior to the rainfall event. If there were few rainfall events within a short period of time, the total rainfall will be observed and will be counted as the total contribution to the changes in the water level in the modules. From the changes of water level, the changes in volume inside the stormwater modules can be calculated by comparing it with the graph for the water level and the occupied volume for the on-site setup. The changes in volume inside the stormwater modules will represent the volume detained by the modules. Hence the efficiency of the detention of the stormwater modules can be calculated using Eq. (4).

$$\%\text{Detain} = \frac{V_D}{\sum V_R} \times 100\% \tag{4}$$

where V_D is the detained volume.

2.3 Determination of Design Rainfall

The observed rainfall from the on-site observation can be compared to the Intensity-Frequency-Duration (IDF) curve or approximation equation developed for Kuching Airport (Station ID: 1403001) [8] which is about 3.5 km from the site. For the purpose of on-site detention, Department of Irrigation and Drainage, Malaysia (DID) [2] recommended a design storm of 10 year ARI (Average Recurrence Interval) in accordance with the minor drainage system ARI. As the on-site setup surface area can be considered as small catchment, hence it was suggested to consider short duration design storms of between 5 minutes to 30 minutes. The calculated design rainfall depths are as presented in Table 1. The calculated design rainfall depth can be compared to the observed rainfall to determine the equivalent ARI.

Table 1 - Calculated rainfall design depth

ARI	Storm Duration (min)	Design Rainfall Depth (mm)
10-year	5	15.3
	10	27.8
	15	38.4
	20	47.6
	25	55.6
	30	62.8

3. Result and Discussion

3.1 Void Ratio and Volume of Stormwater Module

Table 2 shows the relationship between the water level in a single stormwater module used in the current study with the volume without the module structure (TVWS*)*, volume with the module structure (TVS), the net volume and porosity. From Table 2, the average porosity for a single stormwater module used in the current study is 94%. Fig. 4 shows the relationship between net volume and the water level for a single unit module. This porosity value for the stormwater module in the current study is higher than other stormwater modules used in existing literature such as Muhammad et al. [5] with porosity of 75%, Kee et al. [6] with porosity 82% and Mohammadpour et al. [7] with porosity 85%.

For the on-site setup, for an area of 5.0 m (L) x 2.0 m (W); 40 units of the stormwater modules was required. Fig. 5 shows the relationship of the net volume with water level for the on-site setup. From this relationship, the volume of water detained inside the stormwater modules can be determined immediately during the on-site observation for the water level since one side of the setup was made of transparent material as shown in Fig. 6.

Table 2 - Relationship between water level and volume for a single unit of stormwater module in the current study

Water Level (m)	Volume without Structure, TVWS (m^3)	Volume of Structure, TVS (m^3)	Net Volume (m^3)	Porosity (%)
0	0	0	0	
0.03	0.0075	0.00134	0.00616	82.1
0.08	0.02	0.00171	0.01829	91.5

0.13	0.0325	0.00203	0.03047	93.8
0.18	0.045	0.00230	0.04270	94.9
0.25	0.0625	0.00263	0.05987	95.8
0.32	0.08	0.00296	0.07704	96.3
0.37	0.0925	0.00324	0.08926	96.5
0.42	0.105	0.00356	0.10144	96.6
0.47	0.1175	0.00392	0.11358	96.7
0.50	0.125	0.00526	0.11974	95.8
		Average		94.0

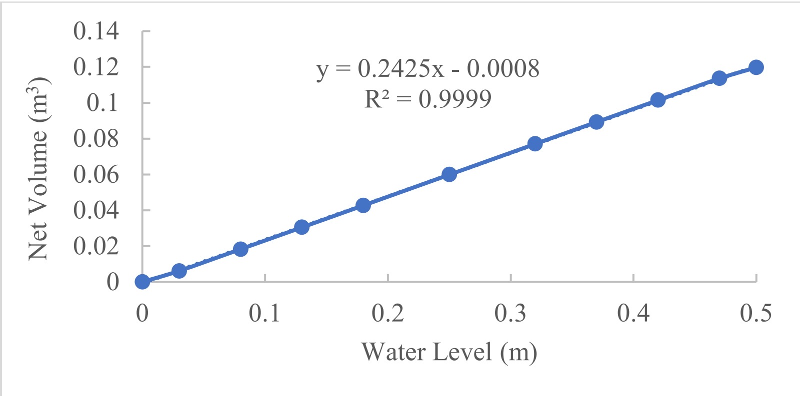

Fig. 4 - Net volume with water level relationship for a single unit of stormwater module in the current study

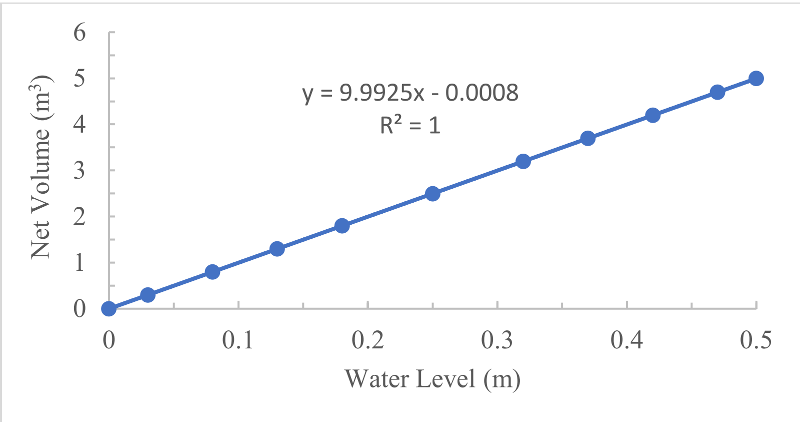

Fig. 5 - Net volume with water level relationship for stormwater modules setup on-site

Fig. 6 - By measuring the water level (shown with white arrow), the volume of water detained

inside the on-site stormwater modules setup can be determined

3.2 On-site Monitoring of Stormwater Modules

Monitoring of the on-site stormwater modules setup was done from 13 April 2021 to 14 October 2021 (6 months). The monsoon season was purposely avoided since it will be hard to quantify the detained volume by the stormwater modules for each rainfall event when multiple rainfall events happened almost everyday during the wet season. During the monitoring period, water level and rainfall data were collected especially after a rainfall event. Not all the water level from rainfall events between these periods were capture due to the sensor not fully functioning when not charged properly with solar. Table 3 shows the summary from nine storm events in the observation period. The data includes the date, total rainfall for the event (with duration), peak hourly rainfall, estimated runoff generated, water level in the stormwater modules for after and before the rain, estimated volume for both after and before the rain as well as the detained volume and percentage detained.

Table 3 - Parameters for observed rainfall events

Storm Date	Total Rainfall (mm) [duration, hr]	Peak Hourly Rainfall (mm)	Runoff Volume (m^3/s)	Water level after rain (m)	Water level before rain (m)	Volume after rain (m^3)	Volume before rain (m^3)	Detained Volume (m^3)	% detained
13 & 14 Apr 2021	20.9 [2 hr]	12.4	0.209	0.27	0.25	2.698	2.498	0.200	95.6
17 & 18 Apr 2021	30.1 [9 hr]	16.9	0.301	0.31	0.28	3.098	2.798	0.300	99.6
28 & 29 Apr 2021	56.8 [4 hr]	49.2	0.568	0.34	0.32	3.397	3.198	0.200	35.2
8 May 2021	25.4 [4 hr]	22.3	0.254	0.40	0.38	3.997	3.797	0.200	78.7
5 & 6 June 2021	11.1 [3 hr]	8.1	0.111	0.48	0.47	4.796	4.696	0.100	90.0
7 & 8 June 2021	48.5 [2 hr]	48	0.485	0.50	0.48	4.996	4.796	0.200	41.2
6 & 7 July 2021	24.6 [2 hr]	24.5	0.246	0.43	0.41	4.297	4.097	0.200	81.2
12 Aug 2021	30.7 [8 hr]	19	0.307	0.53	0.51	5.296	5.096	0.200	65.1
14 Aug 2021	25.6 [2 hr]	25.6	0.256	0.44	0.42	4.397	4.197	0.200	78.1
				Average					73.9

Fig. 7 shows the relationship between the total rainfall and the percentage of the runoff detained inside the stormwater modules.

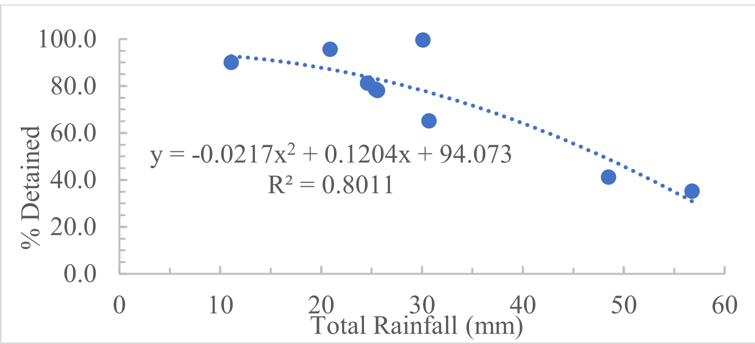

Fig. 7 - Relationship between percentage detained with total rainfall

From Fig. 7, there is a diminishing percentage of runoff volume being detained as the total rainfall increased. This may due to the saturation of the top soil layer for the on-site setup. Higher rainfall may reduce the infiltration rate through the top soil layer due to the increased in saturation. Hence, more volume of rainfall will be converted into surface runoff than infiltrated through the top soil and subsequently being detained by the stormwater modules. The percentage volume of water detained for total rainfall between 11.1 mm to 56.8 mm ranged between 35.2% to 95.6% with a mean value of 73.9%. Comparing this findings to the percentage of volume detained (between 30% to 74%) from the study by Ngu et al. [4] for modular pre-cast concrete stormwater detention system; the current subsurface stormwater modules performed slightly better. This could be due to the top soil layer used in the current study that allows runoff to infiltrate and store in the layer before reaching the subsurface modules. This allows more runoff to be capture as compared to the modular pre-cast concrete detention system where most of the surface are impervious concrete surface. This findings concurred with the findings by Mohd Sidek et al. [3] where the system with infiltration to the surrounding soil performed better than without infiltration.

4. Conclusion

The new stormwater module design used in the current study has been found to have an average porosity of 94%. For the performance of the stormwater modules in terms of detention, it has been found to be able to detained between 35.2% to 95.6% of the total runoff generated by total rainfall of between 11.1 mm to 56.8 mm. Further studies are recommended on the detention performance under different type of top soil locally available in Malaysia, under different slope of the stormwater modules setup as well as the performance under intense multiple rainfall event during the monsoon season with better monitoring equipment.

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