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Research paper

Performance of cylindrical detention pond (CDP) as depression storage under fully saturated condition

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Abstract

Permeable pavements are a key Storm water management measure employed both to attenuate surface runoff in urban areas and to filter urban storm water pollutants. Existing permeable pavements (PP) are design with the specific percentage porosity whereby enabling excess rainwater to infiltrate through the system and acting as a depression storage at the same time. Depression storage basically refers to the volume of water trapped in the depression when the precipitation of a storm reaches the ground and filled up all the depression before it can flow over the surface. Cylindrical Detention Pond (CDP) is an alternative paving material that may alleviate many of the hydrological problems caused by urban runoff from developed areas. CDP consist of three basic component; top cover, bottom cover and hollow cylindrical at centre (300mm thickness). The hollow cylindrical has approximate 50 percent porosity from the total solid of component, which is every 1 inch (25 mm) of pavement depth can hold 0.5 inches (12.5 mm) of rain in theoretical. In this study, the depression storage rate of CDP was investigated under three different rainfall intensity scenarios which are 77mm/hr (low), 153mm/hr (medium), and 230mm/hr (heavy) respectively whereby it function to monitoring the analytical trend line. The experiment was conducted in model box in the laboratory under fully saturated condition. It found that the CDP can perform to detent the water until 180 min of excess rainfall for all 2 year ARI, 5 year ARI, 10 year ARI, 20 year ARI, 50 year ARI and 100 year ARI with different rates. The result was proved the hollow cylindrical at centre of CDP very effective in runoff volume reduction according to the different ARI trend line projection.

Keywords: *Depression Storage; Cylindrical Detention Pond; Permeable Pavement; Storm Water Management; Fully Saturated.*

1. Introduction

In recent years, rapid urbanization changes the land use by removes vegetation, green cover and replaces pervious area with increases in impervious surface with proximity to premix roads and concrete [1]. Since 1970’s, the total population were urban dwellers increases to 30 percent and even more surprisingly in a year 1991, the urbanization had increase the population up to 50 percent and even keep on increasingly from year to year until now. Urban developments will also increase to meet the need of these increasing urban populations. Therefore, the impact of development has become one of the major causes that lead to flooding and the natural hydrologic cycle is disturbed where infiltration rate and ground water recharges decreases, changes imposing high peak flows pattern of surface and river runoff volume increases [1 - 3].
Moreover, not surprisingly rate of flash flood in urban area in Malaysia in generally is expansion severe from year to year. Many urban cities have also increased the speed of overland flow and the amount of runoff because gray infrastructure has been designed to move water off streets as quickly as possible through gutters, storm drains, sewer pipes and other engineered collection systems and is discharged into nearby water bodies. Previously in Sarawak, a conventional drainage system has been designed to provide the fastest possible transport of storm water runoff out of the catchment into the receiving water as an effective mitigation flash flood [4]. Unfortunately, due to rapid development and high rainfall intensities, conventional drainage system, has led to high potential occurrence of flash flood at the downstream of the catchments.
Therefore, permeable pavement (PP) is another alternative approach in stormwater management to replace the conventional impervious concrete and asphalt paver and purposely to prevent physical damage to persons and assets from flooding and to maintain the natural hydrologic cycle, reduce runoff volume, and to decrease peak flow pattern of surface [5]. Therefore, the Environmental Protection Agency (EPA) focuses in studies more specifically to determine the efficiencies of numerous types of PP’s for urban runoff control in the early 1970s. Many researchers have reported that PP’s performances show the decrease peaks flow rate and reduce runoff volume. According to the National Asphalt Pavement Association (NAPA), the concept of PP was suggested to allow percolation, reduce storm sewer loads, reduce floods, raise water tables, and replenish aquifers since the 20th century.
Permeable Pavement are widely suitable for a variety of residential, commercial and industrial applications [6], although it confine to light duty and infrequent usage, but the capabilities of these systems allocate for a large extent range of usage and one of the best alternatives used in stormwater management. Researcher was start to develop the new idea to produce the portable permeable pavement with the futuristic design, color, easy to install and user friendly. There are many variants for each of PP depending on the design goals such as permeable concrete (PC), permeable asphalt (PA), permeable interlocking concrete pavers (PICP), concrete grid pavers (CGP), and plastic grid pavers [4]. However, all the existing of PP is only to help rainfall water infiltrate into the subgrade but not design to store the rainfall water for temporary at the

same time. The major problem for each PP is durability, clogging and depression storage where it will generate back the flash flood problem [7].

PP is one of the active mitigation systems where able to treat runoff from other features on-site as well, including buildings, areas paved with conventional impervious concrete, and buffer zones. The total amount of runoff is less than the total rainfall because a portion of the rain is captured in small depressions in the ground (depression storage), some infiltrates into the soil, and some is intercepted by the ground cover [8]. Moreover, Foster et al. [9] also reported in their studies, that PP with suitable “sub-soiling” (maintenance of a porous layer of soil underneath) be able to reduce runoff volume within 70 to 90 percent and the best medium with the void space that provide temporary storage. However, the temporary storage is only can depend on the depression storage depth. A study showed that the depression storage only can hold back for a plenty of rainfall in the limited time. Depression storage basically refers to the volume of water trapped in the depression when the precipitation of a storm reaches the ground and filled up all the depression before it can flow over the surface. Depression storage is a controlling storage part which contributed for most of the retention on a catchment surface area and does not appear as runoff [10]. Every PP has their owned depression storage and normally the depression storage is depending on the thickness of the pavement and the void ratio.

The advantage of depression storage is the total runoff volume is decreases because a portion of the rain is trapped in small depressions area in the ground (depression storage), and some infiltrates into the subgrade. The size of the depression storage in the PP take a major role in the collection and storage of incoming precipitation, there by modifying the runoff response of a watershed [11]. Moreover, according to the Linsley et al., 1982, the volume of water in depression storage at any time during a precipitation event can be approximated as:

$$V = S_d\,(1- e^{-kP_e}) \qquad (1)$$

Where;
V is the volume of water in depression storage,
S_d is the maximum storage capacity of the depression,
P_e is the rainfall excess, and
k is a constant equal to $1/S_d$

Moreover, the theoretical storage capacity of the PP is based on its effective porosity which can be filled with rain in service. If the PP has 15 percent effective porosity, then every 1 inch (25 mm) of pavement depth can hold 0.15 inches (4 mm) of rain [12].

The storage capacity of a PP system is typically designed for specific rainfall events, which are dictated by local requirements. Therefore, Mannan, et al.[13] produce the latest design for permeable pavement which is called as Cylindrical Detention Pond (CDP) where in physically it easy to install, small scale size, high durability and purposely design for infiltration and as storage function. CDP acting as permeable pavement which is the concept design is to allowed water to infiltrate and the same time as detention. The system consist hexagon shape at top and bottom cover while at the centre is made in hollow cylinder shape which is has approximate 50 percent porosity. However, there are insufficiencies of information regarding the hydrological performance for the system and the depression storage rate at the same time of the system as a PP.

With that in mind, the aim of this study is to investigate the performance of depression storage rate of CDP under variety of rainfall intensity. The exploration starts by outlining the problem relevant to the PP in relation to the current literature and defining the research direction in line with the current body knowledge. A comprehensive investigation was carried out under fully saturated conditions.

2. Material and method

The research and experiments were conducted in a laboratory scale setup developed at the Faculty of Engineering, Universiti Malaysia Sarawak. The experimental was set up as shown in Figure 1 below.

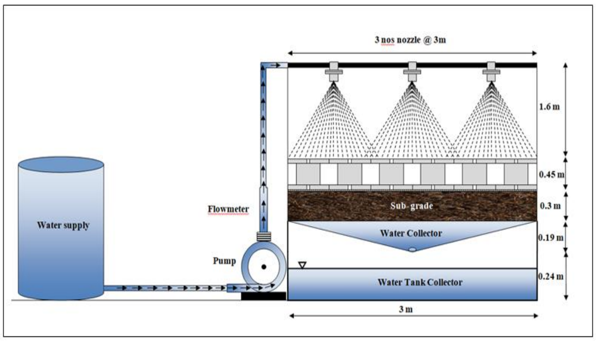


Fig. 1: Schematic Diagram for Experimental Laboratory Setup.

Equipment used to determine the optimum volumes of CDP are, 23 nos of CDP, Green Pavement Box and; and Pavement Box with the size in 3m (Wide) x 1.305m (Length) x 0.96m (Height) were arrange and installed with 23 nos of CDP on the peat soil as shown in Figure 2. The CDP was tested under fully saturated condition in order to determine the optimum volume of cylinder detention pond under various rainfall intensities using three numbers of full cone nozzle types with the outflow capacity up to 27 Liter Per Minute (LPM) in circular spray pattern with 3.58mm of orifice diameter and located in series at height 1.6m centre to centre from surface CDP with the maximum angle distribution up to 103º.

The rainfall intensity was divided into three category i) Low rainfall intensity (77 mm/hr) ii) Medium rainfall intensity (153 mm/hr) and iii) High rainfall intensity (230 mm/hr). The rainfall intensity was performed up to 3 hours and the water depth and volume discharge were recorded for every 1 minute interval.

90 percent density compaction Peat soil as sub-grade in 350mm thickness was layered below the CDP and soak into the water for 24 hours to keep it under fully saturated condition and as a part to maintain the water content and degree of saturation, Sr in 100% (Figure 3). Therefore the outlet of the Green Pavement Box was closed and allowed the vertical movement upward of water only as no infiltration on the sub-grade allowed (Figure 4). The water table of ground water was set up at the same level of the sub-grade. The incremental of water depth and volume discharge were recorded for every 1 minute interval. The reason to keep the subgrade (peat soil) into fully saturated condition is because to ensure there are no infiltrations process occurs on the subgrade and to let the rainwater keep on increasing from the bottom of the CDP system to upward.

Fig. 2: Installation Process of CDP on the Peat Soil.

Fig. 3: Sub-Grade Soaks into Water for 24 Hour.

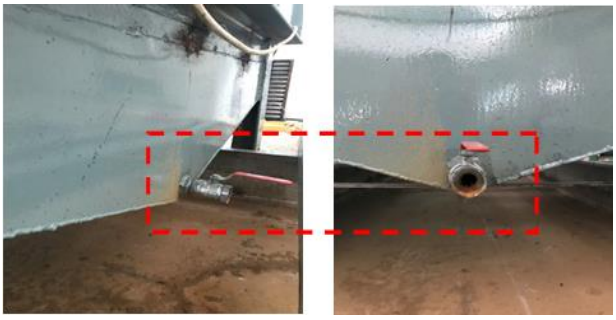


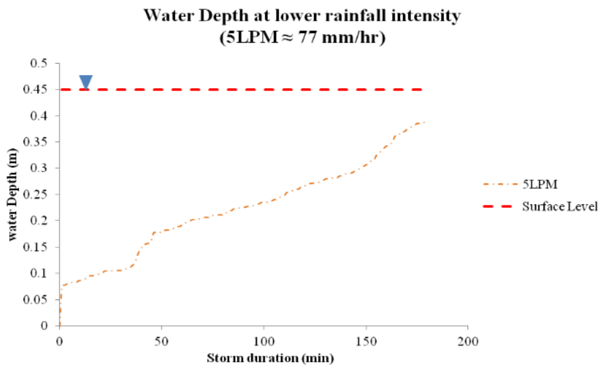
Fig. 4: Outlet Close Panel.

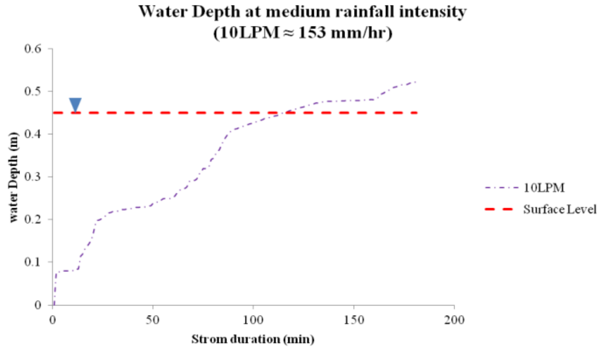
3. Result and discussion

3.1. Water depth versus storm duration (experimental)

Figure 5 shows the experimental curve for time against water depth for CDP under three different type of rainfall intensity (77 mm/hr, 153 mm/hr and 230 mm/hr). Altogether, it can be seen that water depth increases in directly proportional to the time representing for 3 hours duration rainfall. In the view of the result obtained, water start to overflow on the surface of the CDP system after 110 min and 83 min for 153mm/hr and 230mm/hr rainfall intensity respectively. It be realised that the system not able to cater the remaining amount of rainfall for medium and heavy rainfall intensity. However it can be observed that at 77mm/hr rainfall intensity the water depth still below the surface level.

From the result, this indicated that the CDP system only can cater for the specific amount of volume water based on the size design. Previous study has shown that the existing permeable pavement only allowed water to infiltrate into the groundwater but not function as detention but the CDP was designed to able allowed water infiltrate and at the same time to detent the water. However due to the limitation sized design, the CDP only can cater the specific amount of water with the limitation of duration.





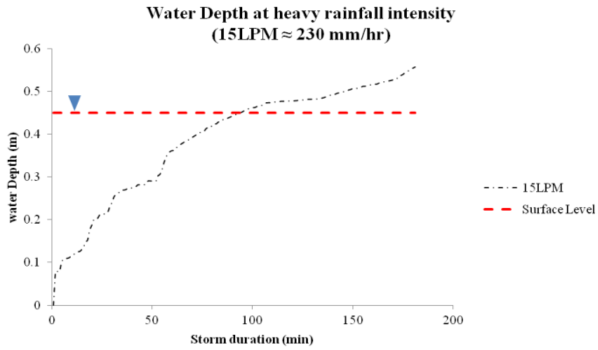


Fig. 5: Experimental Depression Storage Depth at Rainfall Intensity 77 mm/hr, 153 mm/hr, and 230 mm/hr.

3.2. Water depth versus Storm duration (Analytical)

Figure 6 illustrate the estimation analytical ideal water depth. The estimation was conducted according to the mathematical formula to determine the increases of water depth in the CDP system against time. As can be seen from the graph the water depth increases linearly proportional when the time increases until reach the 180 min storm duration. In contrast, it is apparent that the incremental water to reach the surface level for the three type of rainfall intensity tested is fastest compare to the experimental result. This subjected to other reason.

In view of the result obtained, the estimation mathematical formula was conducted in the ideal form which is there are no resistance access such as, the cover, and the path of rainfall to reach at the ground of system compare to the experimental result. Therefore, the water depth increases smoothly without any resistance. As previously discussed the analytical model represents performance in ideal conditions without any the resistance. This is believed that the analytical is a platform to monitor the experimental result in order to see the pattern and the trend of the result was not out of the boundary. Therefore in order to decrease the range between experimental and analytical result, the estimation based on these variable should be noted.

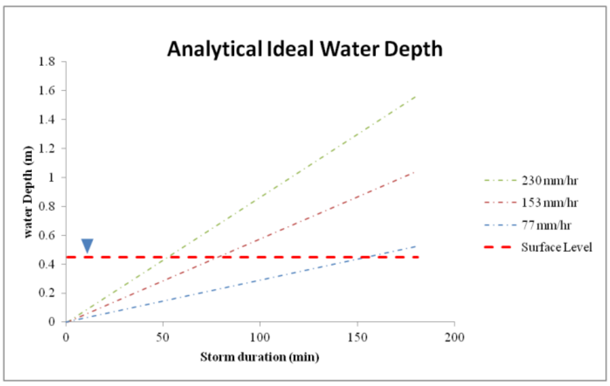


Fig. 6: Analytical Ideal Depression Storage at Three Different Type of Rainfall Intensity.

3.3. Comparison between experimental against analytical trend line (water depth versus storm duration)

Figure 7 shows the trend line between analytical ideal and experimental data for storm duration against water depth. There was little difference between analytical and experimental data for all three type rainfall intensity tested. It can seen that the experimental trend line appear a slightly below the analytical trend line. The decreases of the water depth for experimental were showing the losses of the volume water from the total volume in 3 hour duration. According to the fully saturated condition, the total amount of output volume should be the same amount of input.

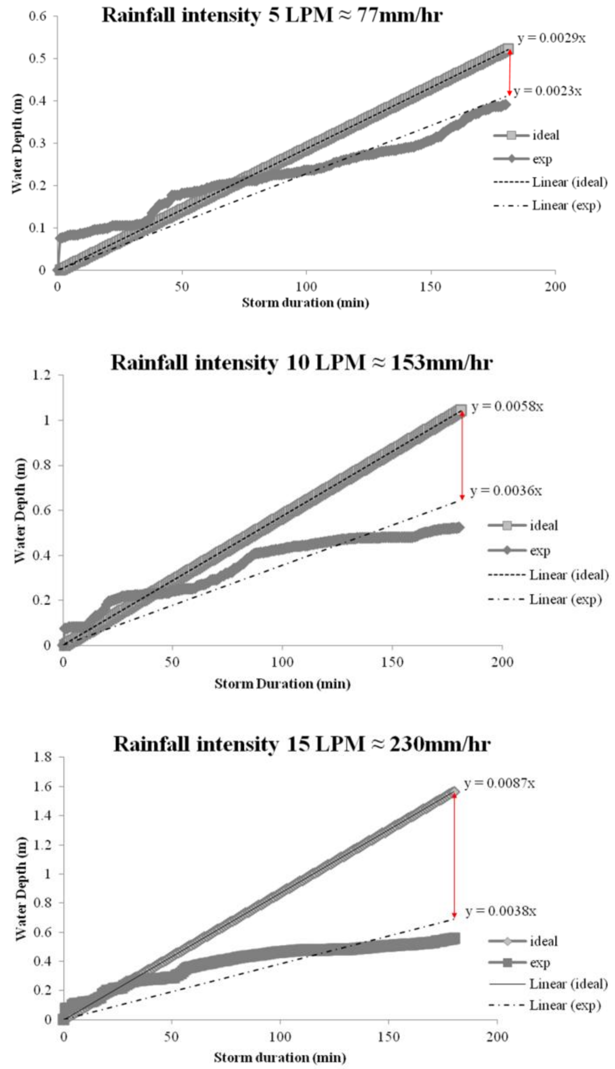


Fig. 7: Comparison Trend Line between Analytical Ideal and Experimental at Rainfall Intensity 77 Mm/hr, 153 Mm/hr and 230mm/Hr.

All the process is deliberate to happen in order to see any possibility of water losses. Therefore, three different rainfall intensity are used on the similar CDP system in order to see the movement of water if the subgrade state is not in fully saturated condition. Water budget concept was applied to this situation.

By referring to the theoretical water budget equation, mass inflow is equal to the mass outflow. However, from the calculation, the total volume after 3 hour rainfall obtained lesser compared to the analytical ideal volume. This reduction related to the volume of collector where it located below to the sub grade which is a part of the component in pavement box. Therefore, from the calculation to verify the reduction of the total amount of water, it was found that the amount of water decreased is equal to the amount of water in the collector and the soil.

Table 1: Total Volume Clarification Distribution

	5 LPM	10 LPM	15 LPM	Unit
Total Volume inflow after 3 hour	0.9	1.8	2.7	m^3
Total Rainfall Volume after 3 hour (Experimental)	0.67	0.9	0.96	m^3
Total volume infiltrate to collector (S_g)	0.71	0.71	0.71	m^3
Total volume trap in the soil (S_{sm})	0.00	0.19	1.03	m^3

Table 1 above showed the clarification distribution of the water losses. The reduction volume at the experimental data showing that the water was flow into the collector which is the amount of volume in the collector is equal to the amount of volume reduction. This could be attributed to the water budget equation where the storage, S consist of three components as surface water storage(S_s), water storage as soil moisture(S_{sm}) and water in storage as groundwater(S_g). Therefore, the reduction volume from the experimental data was showing by infiltration into the groundwater (S_g) and in the soil (S_m) as remaining. At this case, the groundwater was referred to water collector while the soil referred to the subgrade component in pavement box as shown in Figure 7. In addition, the clarification regarding the reduction volume of water outflow was made by proving using the water budget concept and the amount of water at the collector and in the soil is equal to the amount of reduction.

$$S = S_s + S_{sm} + S_g \quad (2)$$

3.4. CDP depression storage performance under various ARI's

Figure 8 shows the water depth of runoff that could be generated on the 3m x 1.305 m experimental project according to different Average Recurrent Intervals (ARIs) and storm durations in Samarahan. It was designed to withstand 3-hour of continuous 10-year ARI design storm. Moreover, from this trend line, it can give the earlier estimation water depth for every single ARI's in designation. Illustrate in the same figure, it shows that the experimental project could capture fully stormwater of lesser and more frequent storms. Moreover, the CDP able to cater the number of volume rainfall up to 180 min storm duration at different rainfall intensity according to the ARI's trend line graph. Therefore, according to this experimental project graph below, the CDP applicable to installed into a large area and still can cater the volume of rainfall. However this graph was applicable for design 3m x 1.305m catchment area. Different of size catchment area will generate a different number of volume rainfalls.

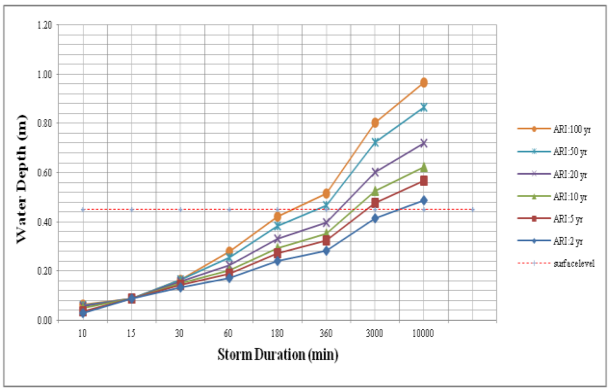


Fig. 8: Generated Water Depth on the Pavement Box (Laboratory Experimental).

4. Conclusion

From the present study, it can be concluded that the CDP system is one of the best alternative in stormwater management as permeable pavement design. This work was devoted to assess the capability of the CDP to predict the optimum depression storage capacity under fully saturated condition. This was performed by investigated the variety of rainfall intensity on the effective catchment area. An experiment was carried out to determine the depression storage capacity of CDP on the fully saturated condition. From the projection graphical trend line of ARI, the CDP can detent the rainfall water up to 3 hour storm duration without any failure. It found that the depression storage of CDP can perform to cater the water until 180 min excess rainfall for 2 year ARI, 5 year ARI, 10 year ARI, 20 year ARI, 50 year ARI and 100 year ARI with different rates. Moreover, it was found that CDP had the greatest permeable pavement in stormwater management according to the projection trend line graph.

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