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Rainfall Characteristics and Its Effect on Road Infrastructure Health

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Abstract: Malaysia has a strategic geographical location in which it is protected from most of natural disasters such as earthquakes and typhoons. However, it is affected by flood which is a common occurrence in Malaysia. There is a direct relationship between rainfall and flooding as the increase in rainfall intensity would produce higher runoff. This research is first focused on the four rainfall stations located at the Northeast District of Penang Island, in which its rainfall pattern was determined from 2007 to 2016 and geospatial data analysis has been done by using ArcGIS. The occurrence of flood is found to have great impact on the road infrastructure health. Next, soil commonly used for road foundation (subgrade) in Malaysia was used to investigate the effect of moisture content on subgrade strength, in which the California Bearing Ratio (CBR) test was carried out with increment of moisture content. The findings indicated that the rainfall pattern in Northeast District of Penang Island was affected by the monsoon seasons, in which the Southwest Monsoon brings in more rainfall from April to September. The extreme rainfall during the Southwest Monsoon caused flood to frequently occur in the study area. Total rainfall in the area indicated a decreasing trend in which the total annual rainfall of the latest five years is less than that of the first five years, from 2007 to 2016. However, the intensity of rainfall can be seen on the increasing trend and this is expected to cause greater soil exposure to moisture. The CBR strength of soil is found to be reduced with the increasing moisture content, as the soil bearing capacity is reduced when the soil become saturated. The reduction in subgrade soil's bearing capacity will affect the performance of the road systems.

Keywords: California Bearing Ratio; flooding; moisture content; rainfall; road infrastructure

1. Introduction

Malaysia is a fortunate country as it has a strategic location that protected it from natural disasters such as earthquakes and volcanoes explosion. However, the most common natural disaster experienced by Malaysia is flooding. Malaysia cannot be excluded from flooding as the flooding event always occurs during the monsoon seasons. It occurs frequently in Malaysia due to continuous high intensity rainfall and the under capacity drainage systems [1]. It was found that there were 3390 people in Kelantan and 4209 people in Terengganu evacuated due to the occurrence of flood in 2014 [2,3]. The rise of water level of rivers in Pahang, Kelantan, Perak and Terengganu due to heavy rainfall lead to the evacuation of about 60000 people in 2014 [3]. Flooding is found to have a great impact on the road infrastructure health. When flooding occurs, the road infrastructure is inundated. Its performance will be significantly affected as the road structure is saturated and the sub-grade soil is weakening due to excessive water in the layer. Malaysian government has spent 100 million Ringgit Malaysia to repair the damaged roads in Kelantan and about 132

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million Ringgit Malaysia to repair roads in Terengganu, which have damaged due to the occurrence of flood in 2014 [3].

The rainfall in Malaysia is influenced by its geographical location, as it is located between the Pacific and Indian Oceans, which tends to affect its climate [4,5]. According to Suri et al. [6], the one-hour rainfall intensity in Malaysia in found to be increased by 17 % from year 2000 to 2007, as compared to the rainfall intensity in 1970s, and the change in rainfall intensity have led to massive flood. The increase in rainfall and heavy rainfall events not only will increase the probability of recurrence of floods in a region but will also lead to the outbreaks of water-borne diarrheal diseases [7]. With the understanding of the characteristics of rainfall, the public is more aware of the occurrence of floods by estimating the rainfall pattern [8].

The rainfall pattern in Malaysia is significantly affected by the monsoon seasons, which are the Northeast Monsoon and the Southwest Monsoon [9]. The Northeast Monsoon occurs from October to March whereas the Southwest Monsoon occurs from April to September, with April and October act as the transition period between both monsoon seasons. Peninsular Malaysia has more significant rainfall characteristics and relatively high rainfall intensity during the Northeast Monsoon, as compared to the Southwest Monsoon [10]. The Southwest Monsoon has lower wind speed than the Northeast Monsoon as most of the winds flow from Sumatra to Peninsular Malaysia, where a rain shelter is provided by the high mountain ranges for the west coast of Peninsular Malaysia [11].

According to [5], flood usually occurs due to the continuous heavy rainfall and the increase in the number of heavy rainfall event will increase the risk of flood [8]. According to [12], the annual Northeast Monsoon season significantly affect the Kelantan River Basin, resulted in the occurrence of severe flooding. It was shown in the statistics that human well-being and economy are significantly affected by the occurrence of floods, as the world not only will experience economic and eco-system damages, but also historical and cultural values loss [13]. According to [8], road infrastructures, bridges and houses are always destroyed due to the occurrence of floods.

Infrastructure health is the ability of the infrastructure to provide intended level of service in safe and cost effective manner, while overcome the hazards it is designed for during its life span, and it is depending on its components, networks, as well as its characteristics and expected performance [14]. According to [15], road infrastructures are very important in a country for national productivity, growth of economy and human well-being. The maintenance and repairing of road infrastructure during and after the occurrence of flooding becomes the public concern and it is the responsibility of local road authorities [16, 17]. The conditions of flood affected road such as its deterioration rate should be evaluated so that the performance of the road infrastructure can be predicted accurately for better decision making and maintenance of the road infrastructure [18].

The sub-grade, which is the lowest layer of road infrastructure, is easily affected by flood, as it has the largest exposure to flood [19]. The major functions of the sub-grade soil are to sustain the traffic load that exerted on it without any damage, and also to drain the runoff water to the roadside or drainage system [20]. The strength of sub-grade soil can be determined by conducting California Bearing Ratio (CBR) test [21]. CBR is the ratio of force needed to cause a circular piston to penetrate the soil from the surface at a consistent rate of 1mm per min, to the force needed for similar penetration into a standard sample of crushed rock [22]. According to [23], the compacted soil will have higher CBR strength with greater penetration force, and the CBR strength tends to reduce with increasing moisture content, especially when the moisture content of soil exceeds the optimum moisture content, as the resistance to the force of penetration is almost become zero. However, when the soil reached its optimum moisture, the sub-grade strength tends to reduce with increasing water content [24]. According to [25], variations in climate and seasons will lead to the variations of moisture in the road infrastructure, and the equilibrium of moisture in the road infrastructure evolves continuously over time.

2. Methodology

2.1 Study Area

Penang is one of the states in Malaysia, which is located at the Northern region of West Coast, Peninsular Malaysia, with longitude of 100.3292° E and latitude of 5.4145° N. It consists of two parts, which are Penang Island and Seberang Perai. Penang state has a total area of 1048 km^2, with total population of 1.75 million as of 2017. It is a state with the nation's highest population densities, which is 1,666.3 per km^2, and also one of the most urbanized states in Malaysia. This research was focused on the Northeast District of Penang Island in which the four rainfall stations were selected to carry out the study. These rainfall stations are Lorong Batu Lanchang, Kolam Bersih Pulau Pinang, Bukit Bendera, and Kolam Takungan Air Itam. The location of each rainfall station is shown in Fig. 1 and the details of each rainfall stations are shown in Table 1.

2.2 Data Collection

Fig. 2 shows the general structure of data collection in this research. There are two types of data were collected, which are the primary data and the secondary data. In this research, the primary data was collected through soil mechanics laboratory testing. The types of testing can be grouped into two, which are the soil classification testing and the soil compaction-related testing. The soil classification testing consists of five different testing, in order to determine the properties of soil.

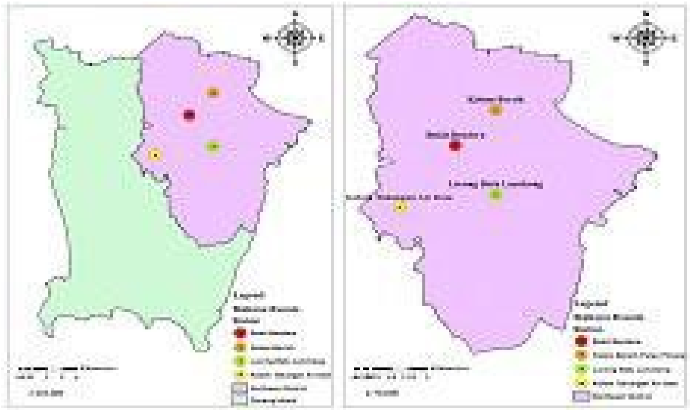


Fig. 1 – Location of rainfall stations

Table 1 – Details of rainfall stations in the Northeast District of Penang Island

Station	Latitud	Longitud	Station Name
5403001	5.402°	100.286°	Lorong Batu Lancang
5402002	5.440°	100.286°	Kolam Bersih Pulau
5402001	5.424°	100.271°	Bukit Bendera
5302003	5.396°	100.250°	Kolam Takungan Air Itam

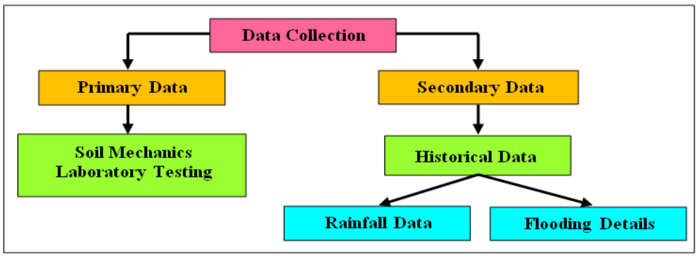


Fig. 2 – General structure of data collection

There are two types of soil compaction-related testing have been carried out, in order to determine the effect of moisture content on the road performance. On the other hand, the secondary data was collected from the Department of Irrigation and Drainage (DID) in Penang Island and also in Ampang, Kuala Lumpur. Two types of historical data were collected from the department, such as the historical rainfall data of the four rainfall stations and also the historical flooding cases which occurred at the study area recently, together with the flooding details. The historical rainfall data was collected in 10 years duration, which is from year 2007 to 2016. After the rainfall data was collected, Microsoft Excel has been used to tabulate the data for further data analysis. However, only the recent years of flooding details were able to collect from the department, which is from year 2014 to 2016. The flooding details were used for geospatial data analysis by using ArcGIS version 10.3, which is one of the software of the Geographical Information System (GIS), in order to determine the location of the flooding cases and its details.

2.3 Soil Mechanics Laboratory Testing

The preparation of soil sample was according to British Standard 1377 - Part 1:1990, “General Requirement and Sample Preparation”. Ten (10) kg of soil sample was dried by using oven-dried method, in which the soil sample was placed in the oven for 24 hours before testing. There were two major types of testing carried out, which are the soil classification testing and the soil compaction-related testing. The purpose of carrying out soil classification testing is to determine the properties of soil sample. Classification tests were carried out in accordance to British Standard 1377-Part 2: 1990, “Classification Tests”. The soil sample was tested for its moisture content, liquid limit, plastic limit and plasticity index, specific gravity and particle size distribution. Soil compaction related testing were carried out to determine the characteristics related to the compaction of soil, and also to assess the empirical strength criterion, which is the California Bearing Ratio (CBR) value of a compacted soil used as a sub-grade material for the construction of pavement. Tests were carried out in accordance to British Standard 1377- Part 4:1990, "Compaction-Related Tests". The Proctor Compaction test was carried out to determine the optimum moisture content of soil corresponding to the maximum dry density, by using a 4.5kg rammer (Modified Proctor). In the CBR Test, The soil sample was prepared in the mould by static compression using tamping method. Three different moisture contents were chosen for the soil in order to determine the CBR strength of soil sample with different moisture content. The chosen moisture contents were 12.2%, 14.5% and 15.5%. A data logger was used in this testing to determine the force at intervals of penetration.

3. Data Analysis and Discussion

3.1 Rainfall Analysis of Northeast District of Penang Island from 2007 to 2016

Generally, there was not much difference of annual rainfall among the four rainfall stations, by comparing the annual rainfall from 2007 to 2016, as shown in Fig. 3. The total annual rainfall of all the stations was found to be in a range between 9318 mm to 12406 mm. Station 5403001 recorded the lowest annual rainfall during the ten years, while station 5402001 recorded the highest annual rainfall, except for 2013. There was only 2106 mm of annual rainfall in 2013 as recorded by station 5402001. Both the station 5302003 and station 5402002 have only two years with the lowest annual rainfall, which are in 2011 and 2014 for station 5302003 and in 2012 and 2015 for station 5402002. It can be seen from the figure that the total annual rainfall of all the stations was fluctuated over the past ten years, which is from 2007 to 2016.

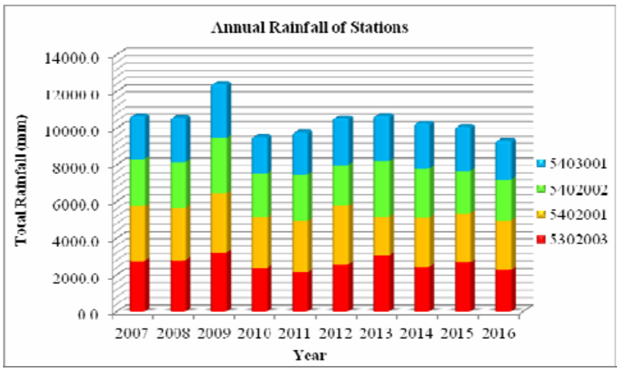


Fig. 3 – Comparison of annual rainfall from 2007 to 2016

However, there was not much difference of total annual rainfall from 2007 to 2016. The highest total annual rainfall was found to be recorded in 2009 while the lowest total annual rainfall was found to be recorded in 2016. There were 12406.5mm and 9318.0mm of rainfall recorded in September and December. The total annual rainfall between 2007 and 2008 was almost the same, which only differ by 79.5mm. There was a significant increase of total annual rainfall from 2008 to 2009, and a significant reduction of total annual rainfall from 2009 to 2010. The total annual rainfall was found to be increased gradually from 2010 to 2013, and reduced gradually from 2013 to 2016. The total annual rainfall from 2010 to 2013 was increased from 9542.0mm to 10678.0mm, whereas that from 2014 to 2016 was decreased from 10275.5mm to 9318.0mm.

The rainfall analysis showed that the highest monthly rainfall usually occurred in September while the lower monthly rainfall always occurred in February from 2007 to 2016, for Northeast District of Penang Island. This is due to monsoon winds seasons which always facing by Malaysia. There are two monsoon seasons facing by Malaysia, which are the Northeast Monsoon and the Southwest Monsoon. Northeast Monsoon is the flow of prevailing wind originating from China and the North Pacific while the Southwest Monsoon originates from the deserts of Australia, towards the eastern and western regions of Peninsular Malaysia respectively. Northeast Monsoon usually occurs from October to March whereas Southwest Monsoon always occurs from April to September, in which April and October are the transition period between the two monsoons. Normally, the Northeast Monsoon tends to bring in more rainfall to Malaysia as compared to the Southwest Monsoon.

Fig. 4 shows the monsoon seasons in Malaysia. During the Northeast Monsoon, the rain brought by the wind monsoon towards the Northeast District of Penang Island is blocked by many other countries such as Thailand and Cambodia. It is also blocked by other states of Peninsular Malaysia, especially the east coastal regions of Peninsular Malaysia, which tend to receive most of the rain. However, during the Southwest Monsoon, the rain is blocked by Sumatra when the wind flows towards the Northeast District of Penang Island. Since Penang Island is located at the western regions of Peninsular Malaysia, the Northeast District of Penang Island tends to receive more rainfall during the SouthwestMonsoon than the Northeast Monsoon.

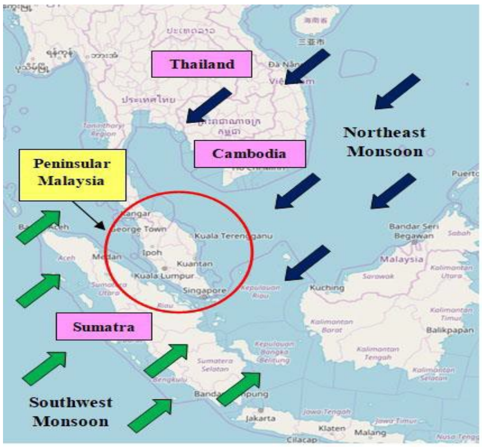


Fig. 4 – Monsoon seasons in Malaysia

Therefore, the Northeast District of Penang Island received more rainfall in September and less rainfall in February for the past ten years. From the rainfall analysis, the rainfall during the Southwest Monsoon basically increased from April to September, while that during the Northeast Monsoon fluctuated from October to March. It was found that substantial rainfall also occurred in the transition periods between both monsoon seasons, which are in April and October. However, the transition period from Southwest Monsoon to Northeast Monsoon, which is from October to November was found to receive more rainfall as compared to that from Northeast Monsoon to Southwest Monsoon, which is from April to May.

Fig. 5 represents the comparison of rainfall during both monsoon seasons from 2007 to 2016. It was clearly shown that the total rainfall recorded during the Southwest Monsoon is more than that during the Northeast Monsoon. There was a significantly increased of total rainfall during the Southwest Monsoon from 2008 to 2009, in which there were more rain being brought to the Northeast District of Penang Island when the monsoon wind flows towards Peninsular Malaysia. On the other hand, there were less rain being brought to the Northeast District of Penang Island during the Northeast Monsoon, as there was a significantly reduction of rainfall in the same year. In overall, it can be seen that the total rainfall during both the monsoon seasons were slightly decreased from 2007 to 2016. This indicated that there was less rainfall being brought to the Northeast District of Penang Island during both monsoon seasons, and it is estimated that the rainfall will continue to reduce for the next few years.

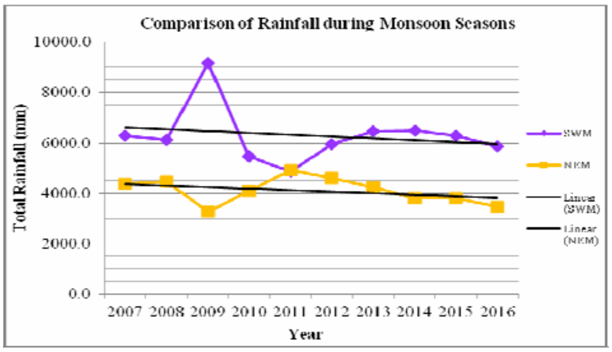


Fig. 5 – Comparison of rainfall during monsoon seasons

This may due to the climate change which tend to increase the air temperature and lead to the reduction of rainfall in the Northeast District of Penang Island. If the reduction of rainfall continues for the next ten years, drought may occur and some of the areas may face water scarcity problems.

Fig. 6 shows the comparison of rainfall for the first five years and the latest five years. It was found that the total rainfall of the four rainfall stations for the first five years is 52979.0mm whereas the total rainfall for the latest five years is 50917.5mm. This indicates that the total rainfall has been reduced by 2061.5mm from the first five years to the latest five years. The difference of rainfall is mostly due to the extremely high rainfall in 2009, which is 12406.5mm. The reduction of rainfall may due to the climate change which has caused the rainfall pattern of Penang Island to be deviated from its original pattern. The climate change has caused more dry periods in the Northeast District of Penang Island, which subsequently reduced the rainfall from 2007 to 2016. The change of climate also lead to the occurrence of extremely high rainfall in 2009. Some areas may receive significantly high or low rainfall throughout the year. When an area is receiving significantly high rainfall, it may lead to the occurrence of flood, whereas drought may occur when some of the areas are receiving relatively low rainfall.

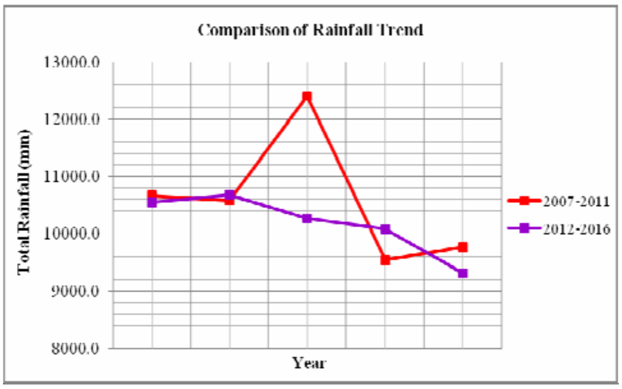


Fig. 6 – Comparison of rainfall between 2007-2011 and 2012-2016

3.2 Soil Classification Testing

Based on the classification of particle size and grading in accordance to British Soil Classification System, it was stated that soil within a range from 0.06mm to 2.0mm is classified as fine soil sand. As shown in Fig. 7, the soil sample can be classified as fine soil sand since most of the soil grain sizes fall between the range. In this case, the values of D_{10}, D_{30} and D_{60} are 0.12mm, 0.33mm and 0.75mm respectively, and they were used to determine the Coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c) of the soil sample, in which C_u is 6.25 and C_c is 1.21. According to the British Standard 5930, a soil with C_u more than 5 and C_c between 0.5 and 2.0 is indicated as a well-graded soil. Since the C_u and C_c of the soil sample have fulfilled the requirements, therefore it is a well-graded soil.

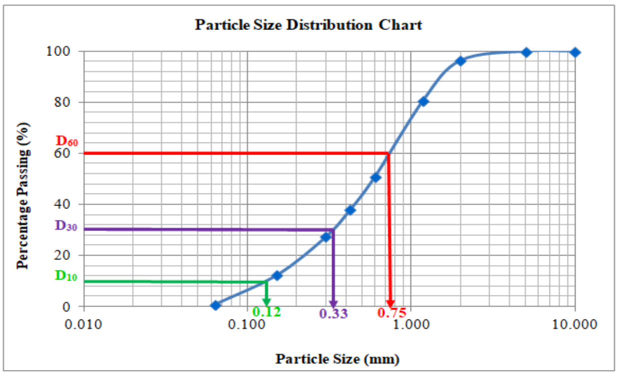


Fig. 7 – Particle size distribution chart of soil sample

After conducting the soil classification testing, the soil was found to have moisture content of 12%. It can be observed through the testing that the soil sample appeared to be in dark brown colour when it was moist. The soil sample has liquid limit of 55.3%, which is between 50% to 70%. Therefore, the soil sample is considered as fine soil sand with high plasticity as its liquid limit was 55.3%. It was also found that the soil sample has plastic limit of 32.8% and plasticity index of 22.5%. The soil is classified as soil with high plasticity as the plasticity index is between 21% and 40%. Besides that, it has specific gravity of 2.77, which is in the range commonly attributed to soil.

3.3 Soil Compaction-Related Testing

Fig. 8 illustrates the relationship between the dry density and moisture content of soil sample. It was found that the dry density of soil sample increased with an increasing moisture content. The dry density of soil sample started to decline after it has reached its maximum. The moisture content corresponding to this maximum dry density is known as the optimum moisture content. The soil sample tends to have maximum moisture content when it achieved maximum dry density as there is no air-voids present in the soil after the compaction process. In this case, the optimum moisture content of the soil sample is 12.2%, with its maximum dry density of $1.92Mg/m^3$.

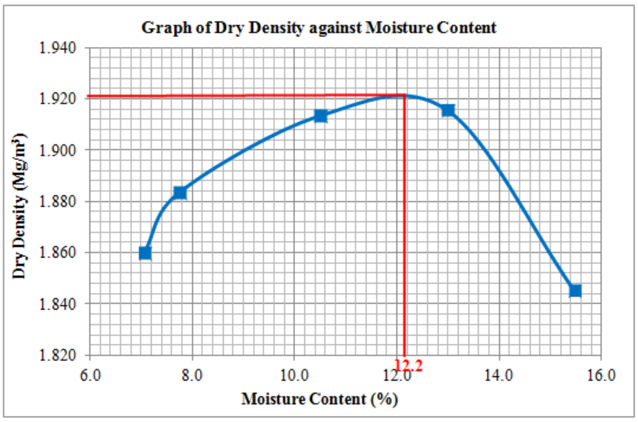


Fig. 8 – Relationship between dry density and moisture content

From the results, it can be observed that the compaction of soil has increased its density with an increasing water content presence in the soil, until both the density and water content reached their maximum value. This has reduced the air-void that available in the soil and reduced its permeability. The soil with low permeability tends to prevent the water particles from passing through the soil easily. In a real circumstance, the road infrastructure are usually compacted during construction so that the rain water will not pass though the road structure easily. This is because the performance of road infrastructure deteriorated when it has been exposed to more water as the moisture content of the sub-grade soil will be increased. The increase of moisture content tends to reduce the ability of road to withstand the maximum load at which it was designed to. The lesser the air voids available in the soil, the higher the strength of the road.

Fig. 9 and Fig. 10 show the comparison of CBR strength of soil sample with different designed moisture content, at penetration of 2.50mm and 5.00mm. Both figures have a similarity in which the CBR strength of the soil sample reduced with increasing moisture content. This indicates that the performance of soil tends to deteriorate when there is more water available in the soil. As tested in the Proctor compaction testing in the previous section, the soil sample has an optimum moisture content of 12.2%. The moisture content which is more than the optimum moisture content will cause excessive water to present in the soil sample as the soil has absorbed the maximum amount of water. The presence of excessive water in the soil will reduce the capability of the soil to withstand the load that being exerted on it.

The soil is expected to achieve maximum density and strength when compacted under optimum moisture content. The strength of the soil will be reduced when there are excessive water present in the soil. The excessive water will cause the soil to become saturated, and the performance of road tends to deteriorate when the soil is saturated with water. This is because the sub-grade soil tends to provide optimum service when it is in an unsaturated condition [20]. In a real situation, the compacted sub-grade soils are firstly in an unsaturated condition after compaction, but they may fluctuated between a saturated and unsaturated over time, due to the climatic condition [20]. When there is excessive water, the CBR strength of soil tends to reduce with increasing moisture content. When the moisture content exceeds the optimum moisture content, the soil lost its ability to resist the load exerted on it as the penetration resistance was approximately zero. Therefore, the CBR strength of soil reduced with increasing moisture content. It can also be explained in such a way that a soil with optimum moisture content tends to have the highest bearing capacity. Once the optimum moisture is exceeded, the soil will lost its bearing capacity with increasing moisture content. Thus, the soil with lower bearing capacity will have lower CBR strength.

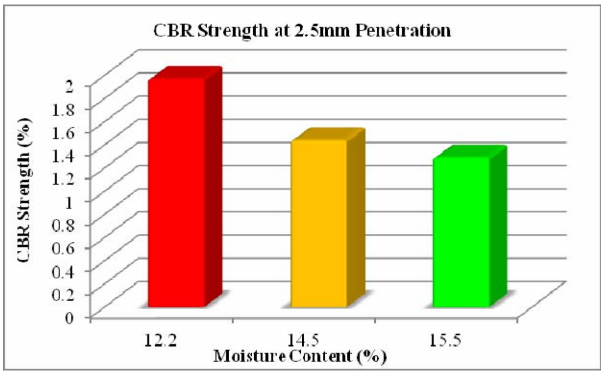


Fig. 9 – CBR strength at 2.5mm penetration

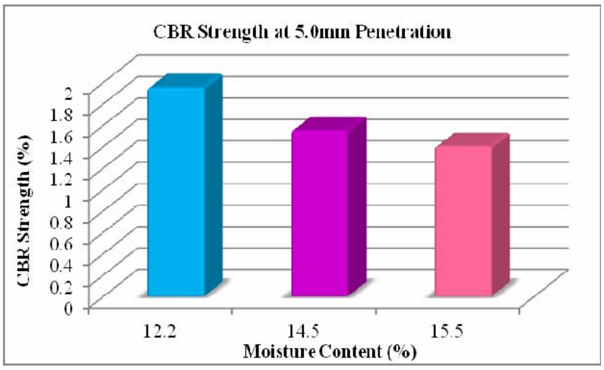


Fig. 10 – CBR strength at 5.0mm penetration

3.4 Relationship Between Rainfall, Flood and Road Infrastructure Health

3.4.1 Relating Rainfall to Road Infrastructure Health

Generally, the rainfall station with more rainfall will have more impact on the road infrastructure. This is because the rainfall station which recorded more rainfall will cause the road infrastructure at the surrounding area to be exposed to more rain water. Fig. 11 shows the comparison of total rainfall of each station from 2007 to 2016.

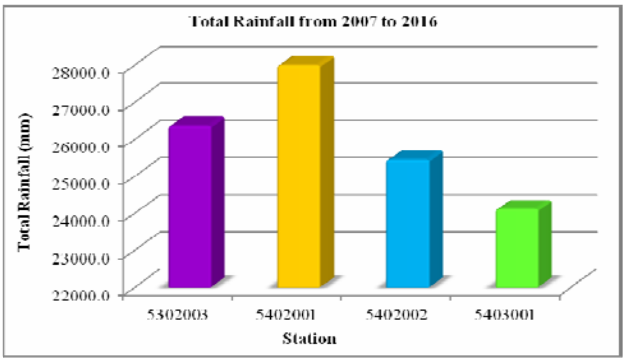


Fig. 11 – Total rainfall from 2007 to 2016

It can be seen that Station Bukit Bendera has the highest total rainfall for the past ten years, which is 27992.5mm, followed by Station Kolam Takungan Air Itam with total rainfall of 26354.0mm. Station Lorong Batu Lanchang has the lowest total rainfall from 2007 to 2016, which is only 24105.5mm. The difference of rainfall among the rainfall stations is due to their geographical location, in which the station located at the higher area receives more rainfall than the low lying area. This is because the temperature at the higher area is less than that at the lower area. In this case, Station Bukit Bendera has recorded more rainfall than the other stations as it is located at the highest area above the sea level.

There is a direct connection between rainfall and moisture content in the road infrastructure. In comparison, the surrounding area of Station Bukit Bendera will be exposed to more rain water, which subsequently caused the road infrastructure to be exposed to more moisture. This may increase the moisture content of the road infrastructure and cause it to face higher risk of deterioration, especially when continuous heavy rainfall occurs. The performance of road infrastructure will be affected with increased moisture content, as the CBR strength of the sub-grade soil will be reduced. This is because when the moisture of soil exceeds the optimum moisture content, there will be excessive water presence in the soil as all the air-voids within the soil particles have been filled up by the water. The excessive water caused the soil to become saturated and this may lead to reduction of soil bearing capacity. Therefore, the performance of road infrastructure is deteriorated as its capability to withstand load decreased [19].

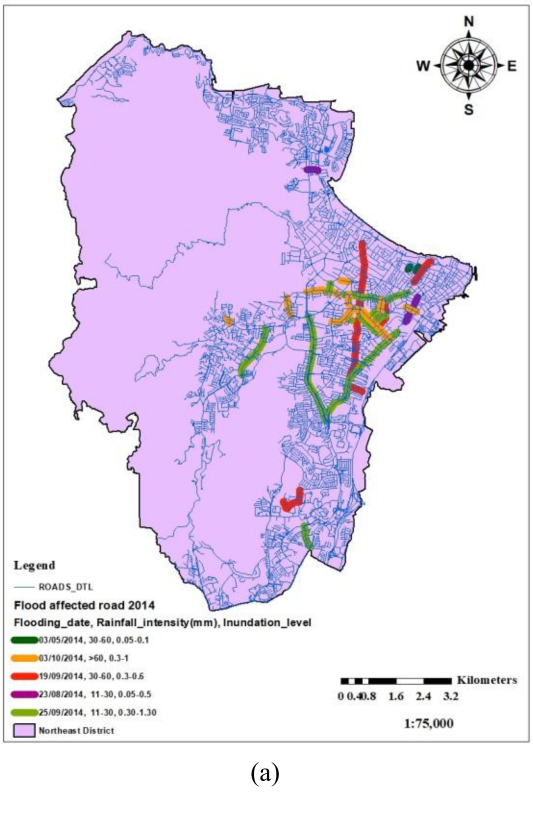
On the other hand, the balance of moisture in the road infrastructure changes over time. The sub-grade soils are usually compacted close to their optimum moisture content during the construction in order to achieve maximum dry density. However, there will be changes occurred on the moisture content in which it will achieve a natural equilibrium state where the moisture content will be lower than the optimum moisture content after the construction is completed [25]. The changes of moisture content are usually depends on the climatic conditions such as rainfall. Therefore, when it is raining, the rain water tends to fill up the air voids available within the soil particles. When all the air-voids have been filled up, the soil has achieved optimum moisture content and the additional rain water will cause the moisture of soil to exceed the optimum moisture content. In this case, the ability of the soil to sustain load decreases with increasing soil moisture. Thus, the performance of road infrastructure deteriorated as the CBR strength reduced with increasing moisture in the soil.

3.4.2 Relating Rainfall to Road Infrastructure Health

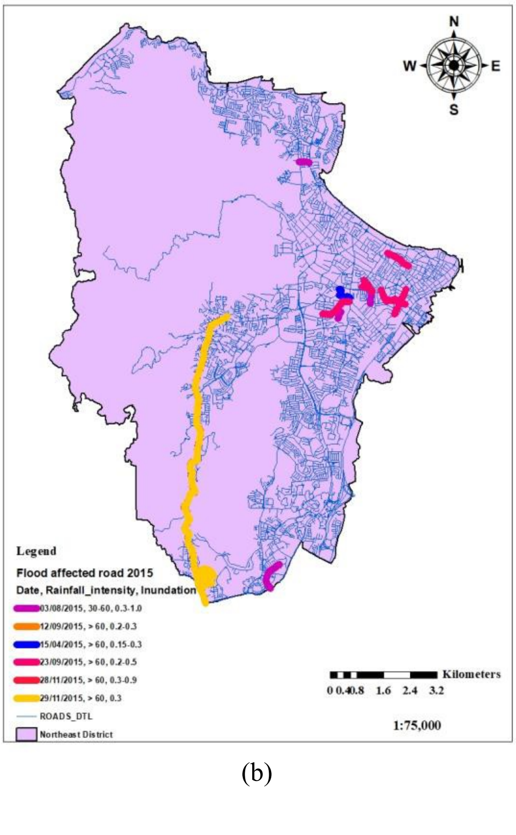
When heavy rain happens in an area, there is a possibility that flood will be occurred at the area. The occurrence of flood is influenced by several characteristics of the rain event, such as the rainfall intensity and duration of rain event. Rainfall intensity is the amount of rainfall in one hour duration. Rainfall intensity can be related to flood by considering the water level of river, in which the occurrence of flood depends on the river level. The water level of river tends to remain at the normal level when there is little rain or no at all. However, when rain event happens with moderate rainfall intensity, it will cause the river level to rise significantly above the normal level and reach the alert level. The river level reaches the warning level when the rainfall intensity is categorized as heavy, and this is the level in which the river level is increasing and near to flooding level. At this level, there is a possibility of flood occurs and the residents shall be prepared for any evacuation action. If the rain event is continuing and the rainfall intensity becomes very heavy, the rise of river level tends to cause considerable flooding and the evacuation action should be initiated so that the residents can be away from the flooding area and move to a higher land. On the other hand, the duration of a rain event will also lead to the occurrence of flood. The longer the rain event, the higher the flood risk. Heavier rainfall tends to cause more severe flooding with higher rain event duration.

Fig. 12a to Fig. 12c show the location of historical flooding cases from 2014 to 2016. The different colours of lines in each figure indicated the date of each flooding cases, with their respective rainfall intensity and depth of flood water. There were five flooding cases in 2014, in which the flood occurred on 3rd of October was due the heaviest rainfall as compared to others, which is more than 60mm per hour. The very heavy rainfall has cause the occurrence of flood in some of the areas with inundation level between 0.3m to 1.0m, which was considered as a serious flood.

On the other hand, another serious flood was occurred on 25th of September with inundation level between 0.3m to 1.3m, but the rainfall intensity was only within 11mm to 30mm per hour, which is considered as light rainfall intensity. There were total six flooding cases happened in 2015, in which most of the flooding cases occurred due to very heavy rainfall intensity, which is more than 60mm per hour. These flooding cases have inundation level which is less than 0.5m, therefore the flood was considered as light flood. However, the flood which occurred on 3rd of August was considered as serious flood, as the inundation level has reach to 1.0m, due to heavy rainfall with intensity between 30mm to 60mm per hour. Besides that, the flood in 2016 occurred due to heavy and very heavy rainfall intensity. The most serious flood in 2016 happened on 29th of October, as the flood level has reached to 1.2m in some areas, due to very heavy rainfall. In overall, it can be said that a serious flood usually occurred due to heavy rainfall which is more than 30mm per hour. The higher the rainfall intensity, the more serious is the flood.



(a)



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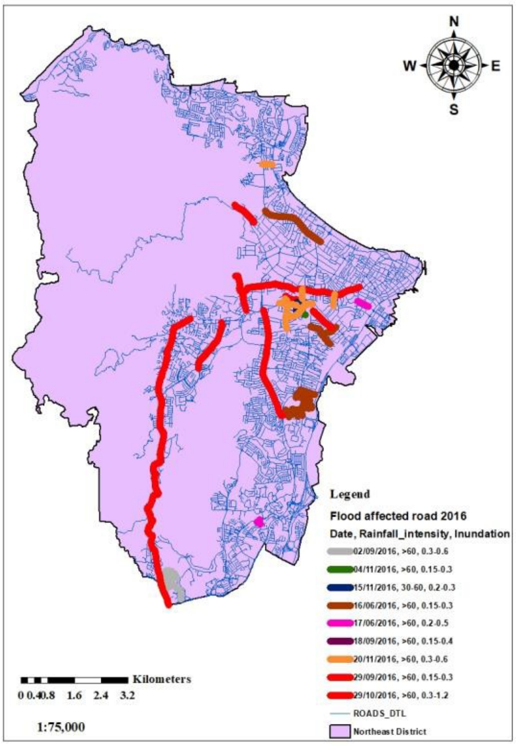

(c)

Fig. 12 – (a) Rainfall intensity and depth of flood in 2014; (b) rainfall intensity and depth of flood in 2015; (c) rainfall intensity and depth of flood in 2016

Table 2 tabulated the number of flooding cases from 2014 to 2016. It was shown in the table that the flooding cases occurred most frequently in September from 2014 to 2016, in which there were 2 cases each in 2014 and 2015, and 3 cases in 2016. It was followed by 2 cases in 2015 and 3 cases in 2016 for November. There were more flooding cases occurred from April to September as compared to that from October to March. This is because there is more rainfall during the Southwest Monsoon comparing with the Northeast Monsoon. Besides that, the number of flooding cases has increased from 2014 to 2016, in which there were total 9 flooding cases occurred in 2016, which is the highest number. The comparison of total monthly rainfall of the four rainfall stations from 2014 to 2016 is established in Fig. 13.

Table 2 – Number of flooding cases

Month	2014	2015	2016	Total
J	-	-	-	0
F	-	-	-	0
Mar	-	-	-	0
A	-	1	-	1
May	1	-	-	1
J	-	-	2	2
J	-	-	-	0
Aug	1	1	-	2
S	2	2	3	7
O	1	-	1	2
Nov	-	2	3	5
Dec	-	-	-	0
Total	5	6	9	2

September as compared to that from October to March. This is because there is more rainfall during the Southwest Monsoon comparing with the Northeast Monsoon. Besides that, the number of flooding cases has increased from 2014 to 2016, in which there were total 9 flooding cases occurred in 2016, which is the highest number. The comparison of total monthly rainfall of the four rainfall stations from 2014 to 2016 is established in Fig. 13.

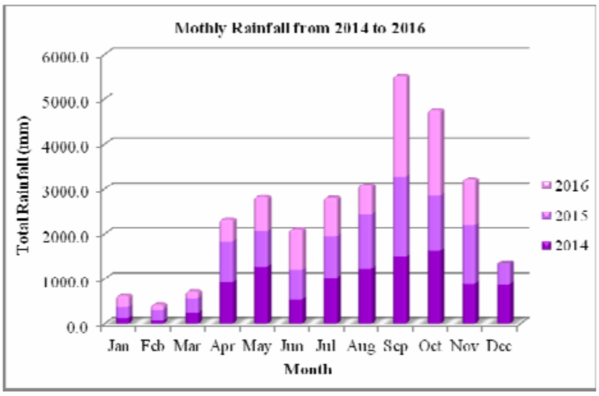

Fig. 13 – Comparison of monthly rainfall from 2014 to 2016

Obviously, September has the highest total rainfall in every year from 2014 to 2016, following by October and November. The first three months usually have the lowest total rainfall as compared to other months. Besides that, the Northeast District of Penang Island received more rainfall from April to September than that from October to March for the past three years. Thus, there are more flooding cases occur between April to September.

Fig. 14 shows the comparison of rainfall intensity of floods at Jalan P. Ramlee from 2014 to 2016. Jalan P. Ramlee was found to experience the highest frequency of flooding event from 2014 to 2016. It has experienced total 14 numbers of flooding events from 2014 to 2016. It was shown in the figure that the rainfall intensity of the flooding events increased from 2014 to 2016, in which the flooding events in 2014 has lower rainfall intensity as compared to that in 2016. This indicates that the occurrence of flood at Jalan P. Ramlee is getting more serious from 2014 to 2016 as the rainfall intensity has been increased.

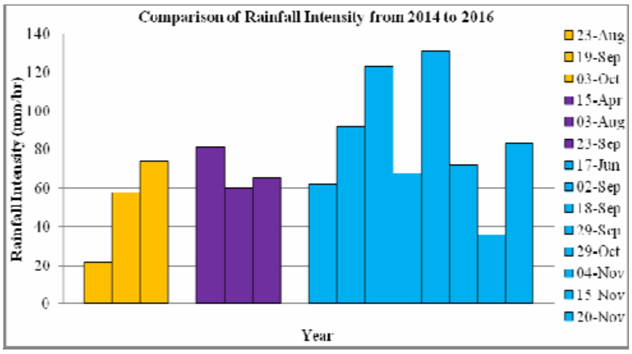

Fig. 14 – Rainfall intensity of floods at Jalan P. Ramlee

It was also found that the number of flooding events has been increased from 2014 to 2016, which means more floods have occurred at Jalan P. Ramlee from 2014 to 2016. This is because the continuous heavy rainfall caused the rainfall intensity to increase, and exceed the absorptive capacity of soil and flow capacity of rivers, the river water will be overflowed easily and lead to flooding.

3.4.3 Relating Flood to Road Infrastructure Health

Table 3 shows the frequently flood affected road from 2014 to 2016, which are Jalan P.Ramlee, Jalan Maccallum, Lorong Singgora, and Tingkat Hock Hin. It was found in this study that flood usually occurred in the Northeast District of Penang Island during the Southwest Monsoon from April to September, especially September which has the most number of flooding cases from 2014 to 2016. The occurrence of flood has affected the road infrastructure at the flood affected area. Based on this study, the most frequently flood affected road was found to be Jalan P. Ramlee, which has been inundated for 14 times due to the occurrence of flood from 2014 to 2016. It has been inundated for three times each in 2014 and 2015, and as much as eight times in 2016. The heavy and continuous rainfall has caused Jalan P. Ramlee to be flooded frequently and the surrounding areas has been affected due to the occurrence of flood. Jalan P. Ramlee is easily flooded as it is considered as low lying area. When there is heavy and continuous rain, the river basin overflows easily and flood will occur. The low-lying areas will always be flooded first than the higher areas.

Table 3 – Frequently flood affected road from 2014 to 2016

Ar	201	201	201	Tot
Jalan P. Ramlee	3	3	8	1
Jalan Maccalum	3	1	1	5
Lorong Singgora	2	1	3	6
Tingkat Hock Hin	3	1	4	8
Tot	11	6	1	3

The flood incident can always be related to the rainfall. When it is raining, the rain water will be absorbed by the pavement and fills up the air voids within the soil particles in the road sub-grade. This will increase the moisture content of the road sub-grade as it always has moisture content which is less than the optimum moisture content. Once all the air-voids have been filled up, further absorption of rain water will cause the moisture content of sub-grade soil to exceed the optimum moisture content. The soil becomes saturated due to the presence of excessive rain water and flood will occur due to the continuous rainfall. The increase in moisture content of sub-grade soil usually tends to increase the CBR strength of the road infrastructure until it has achieved the optimum moisture content. Further increase of moisture content will cause the CBR strength starts to reduce as the soil bearing capacity reduces when the soil become saturated. This is because the capability of the road sub-grade to sustain the load applied on it has been reduced. Thus, the performance of road infrastructure is deteriorated. Based on the research by [18], the rate of deterioration of the structural strength and surface conditions will be increased when the frequency of extreme rainfall and flooding events increased.

Other than that, the road infrastructure which is exposed to repeated flooding will further affect its performance. The road stated in Table 3 has been exposed to repeated flooding incident from 2014 to 2016. When a road is exposed to repeated flooding, the repetition of wetting and drying process will further reduce the performance of the road structure [26]. This is because the sub-grade soil loses its bearing capacity and it will eventually collapse after a few cycles of wetting and drying, as its ability to withstand load has been reduced throughout the process. The soil will become weak due to the presence of water in the soil and it may lead to sub-grade failure as the necessary stability is not maintained by the soil [20]. When the road sub-grade is mostly saturated with water, its strength can be affected as it is highly dependent on the moisture content. Therefore, the performance of Jalan P. Ramlee is the most affected as it has been exposed to the highest number of flood repetition. When a road is inundated due to flooding, the sub-grade strength of the flood affected road is significantly reduced, which lead to the deterioration of road. The road with weakened sub-grade condition tends to deteriorate rapidly once the road is used by traffic.

4. Conclusion

In conclusion, the Southwest Monsoon brought in more rainfall to the Northeast District of Penang Island as compared to the Northeast Monsoon. The total rainfall recorded from April to September was higher than that recorded from October to March for all the rainfall stations. The rainfall recorded during the Southwest Monsoon basically increased from April to September while that during the Northeast Monsoon fluctuated from October to March. However, the transition period from Southwest Monsoon to Northeast Monsoon, which is from October to November was found to receive more rainfall as compared to that from Northeast Monsoon to Southwest Monsoon, which is from April to May. A fluctuating trend of annual rainfall can be observed for all the stations from 2007 to 2016. However, the total rainfall of the first five years, which is from 2007 to 2011, was more than of the latest five years, which is from 2012 to 2016. It was found that there were more flooding cases occurred during April to September as compared to that during October to March, from 2014 to 2016. Jalan P. Ramlee was the most frequently flood affected road, resulted from continuous heavy rainfall. On the other hand, The CBR strength of the soil sample reduced with increasing moisture content. This indicates that the performance of soil tends to deteriorate when there is more water available in the soil. There is a direct relationship between rainfall, flood and road infrastructure health. When it is raining, the rain water will be absorbed by the pavement and fills up the air voids within the soil particles in the road sub-grade. This will increase the moisture content of the road sub-grade and causes the CBR strength of the road infrastructure to increase until it has achieved the optimum moisture content. Further increase of moisture content will cause the CBR strength starts to reduce as the soil bearing capacity reduces when the soil become saturated. Once the capability of the road sub-grade to sustain the load applied on it is reduced, the performance of road infrastructure is deteriorated.

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