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Effect of Climate Change-Driven Tidal Dynamics on The Stability of Senggarang Coastal Embankment

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Abstract: Coastal areas can be described as one of the areas that where it is environmentally sensitive where the ecosystem and local inhabitants may be exposed to some threats such as erosion. Wave erosion and flooding during and after large tidal events were serious risks to the Malaysian coastline in 2000. The Senggarang embankment is facing severe seepage phenomena which could lead to collapse and critical flooding risk where rising sea level is happen. The seepage problem has severely compromised the stability and safety of the embankment, especially where the inland area is flooded during tide. Hence, this study will be focusing on the climatic factor that leads to the problem. The objectives of this research are to examine the tidal dynamics for the past decade at Senggarang Coastal Embankment (SCE) in relation with climate change via analysing data from past case study and literature review and to develop the Failure Risk Assessment tool for Senggarang Coastal Embankment (SCE) due to the sea level assessment and projection using Plaxis. In this study, the embankment was modelled by the use of PLAXIS software program. PLAXIS 8 is a finite elements package used for the two-dimensional analysis of deformation and stability in geotechnical engineering. In summary, it was found that discharge of seepage for embankment constructed with original condition of embankment and present condition of embankment. The projection of mean sea level also being plotted in a graph and being analyze accordingly. The higher the water level, the higher the discharge of seepage. Rising in sea level seems to lower the strength of the embankment by increase in displacement, effective stress, excess pore pressure and seepage. Therefore, climatic factor does lead to failure of Senggarang embankment.

Keywords: Embankment, Climate Change, Rising Sea Level, Failure Risk Assessment

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1. Introduction

Coastal areas can be described as one of the areas that where it is environmentally sensitive where the ecosystem and local inhabitants may be exposed to some threats such as erosion [5]. One of the major threats to the Malaysian coastline in 2000 was the patterns of wave erosion and floods during and after strong tidal occurrences. According to the Malaysian government in 2001, rainfall changes in pattern, climate change, sea-level rise and drought patterns, all contribute to coastal issues. Figure 1.0 shows that the rising sea level happened across Malaysia and being a threat to the coastal area and need action to be taken. The improper design will lead to an embankment that is submerged under the rising sea level [9]. The long duration of the rainfall and high intensity inducing soil erosion and becoming one of the factors that could trigger a failure of slope in the embankment [11]. Earth bank, known as embankment, will usually face the threads, especially in the coastal area due to rising sea levels. Significant embankment failures may occur as a result of surface erosion caused by overtopping flow or interior erosion, which contributes to two problems: seepage and plumbing.

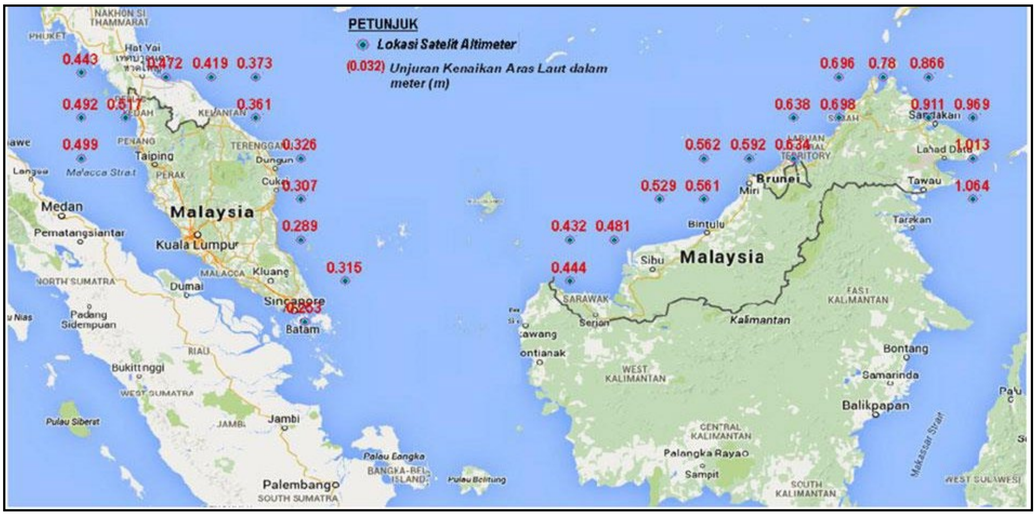


Figure 1: Mean Sea level projected (red indicates elevation relative to mean sea level) for the year 2100 at thirty satellite altimeter locations along Malaysia's coast [6]

Between 2009 and 2010, the National Hydraulic Study Institute (NAHRIM) conducted research on the sea's response to climate change. The research, which spanned many years along the Malaysian coast, intended to evaluate the effect of climate change on rising sea levels. According to the data, by 2040, there would be a considerable sea level increment of between 0.07 and 0.14 m (as a proportion of mean sea level). For 2100, an average sea level increase of 0.25 to 0.52 m is predicted [6].

There is a factor that affected climate in Peninsular Malaysia, and the factor is monsoons. It can be divided into two in one year, the first is from May to September, which is called Southern Monsoons, and the second is from November to March, which is Northeast monsoons. During a transition period of the monsoons, usually around April and October, this period does receive heavy rainfall [4]. Data from past research shows that climate change in Malaysia and even worldwide is worsening. This would lead to more problems across the coastal area. Via data from reliable sources, the objectives of this project are to examine the tidal dynamics for the past decade at Senggarang Coastal Embankment (SCE) in relation with climate change via analysing data from past case study and literature review. Secondly is to develop the Failure Risk Assessment tool for Senggarang Coastal Embankment (SCE) due to the sea level assessment and projection using Plaxis. Figure 2 shows inundation and flooding of the inland due to seepage in 2020 and Figure 3 shows flooding of the inland due to seepage in December 2021.

Figure 2: Inundation and flooding of the inland due to seepage in 2020 [2]

Figure 3: Flooding of the inland due to seepage in December 2021

2. Materials and Methods

Figure 4 depicts the study's methodology flow chart. The rising mean sea level data being plotted into graph and the Plaxis simulation for failure risk assessment simulate to get a data of study.

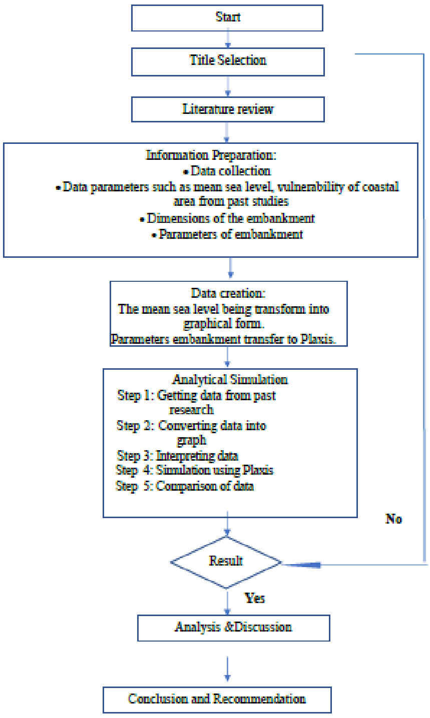


Figure 4: Methodology flowchart

2.1 Data of mean sea levels

The data utilised span a period of 19 years, beginning in 1993 and ending in 2011. The raw data is transformed into a graph for data collected from tidal stations in Johor Bahru, Sedeli, Tanjung Kling, Pelabuhan, Klang Lumut, and Kukup, among other places. In a graph with a regression line, the data will be displayed, and the regression line will be used to simplify the graph and make it easier to observe the trend of the rise and fall values in the graph and the gradient of the graph. In this study, the regression line was identified using the least squares criterion, which is a statistical technique. Because of the use of the concept of least squares, it was possible to ensure that the sum of the squared deviations was maintained to an absolute minimum. Here, the variable y is the variable that can be computed using the relationship for every given value of the variable. The linear regression line is represented by the equations in the following section:

Equation of straight line:

$$y = a + bx \quad Eq. 1$$

2.2 Type of soil use for Plaxis simulation

Since the foundation of the embankment was discovered to be problematic, resulting in an extensive seepage channel inside the embankment. The embankment was designed using two layers with using the bedrock as the foundation and soil at the height of 6 meters and silty clay at the height of 3 meters, respectively. Thus, to see the effect of climatic change factors and the effect of rising sea level, the simulation was run using different levels of water and foundation. Then, PLAXIS will simulate the embankment's seepage analysis.

2.3 Materials sets

Lack of historical records and the large number of repair operations that have been performed over the years in this research led to all of the data and parameters utilized for the simulation being derived from the literature and previous work with only using secondary data as references. Some of the information was gathered via hand calculations.

The material set allows selecting material and model from a material model box. To simulate the stability of the embankment, a model and material parameters must be assigned to the geometry. PLAXIS collects soil characteristics into material data sets, which are kept in a material database. The embankment has two material layers. Three geometric models of embankments were simulated for 1 m, 2 m, and 3 m water levels. The Table 1 below shows data of parameters for the embankment.

In this simulation, load that applied on the embankment will be 2.22 kN/m^2. The embankment was built in 2 conditions, which is the original condition and present condition. The original condition represented the perfect original condition of the embankment when it was first built, while the present condition is the current condition of the embankment after several years. To indicate the failure of the structure in the embankment, a modification was made for the present condition of the embankment where the Young Modulus is being manipulated. Young Modulus for the original condition is set to be 1300 kN/m^2, while for the present condition, the Young Modulus decreased by half to weaken the strength of the embankment and show the present condition of the embankment. 650 kN/m^2 is the new Young Modulus for the silty clay on the embankment.

Table 1: Parameters of Silty Clay and Igneous for bedrock [14]

Parameter	Name	Silty Clay	Bedrock (Igneous rock)

		General	**Granite**
Model		Mohr-Coulumb	Linear Elastic
Drainage type		Drained	undrained
Dry unit weight	γunsat	16	26.6
Bulk unit weight	γsat	17	27
		Parameters	
Friction angle	φ	34	39.1
Cohesion	c_{ref}	14	1100
Poisson ratio	υ	0.34	0.28
Young Modulus	E_{ref}	1300	$5.07x10^7$
		`Groundwater	
Horizontal permeability	k_x	0.778	0.52
Vertical permeability	k_y	0.864	0.49

3. Results and Discussions

The results for analysis on mean sea level will be presented in terms of graph with linear regration to shows the trends over the years of 1993 to 2011.The results that have been observed in PLAXIS software were total displacement, effective stress, excess pore pressure, and discharge of seepage.

3.1 Sea Level Rise

Analysis on mean sea level will be presented in terms of graph with linear regration to shows the trends over the years of 1993 to 2011. The graph can represent and split into 2 parts where a study of 19 years of mean sea level with the climatic events that contributed to the fluctuation in the mean sea level graph trend.

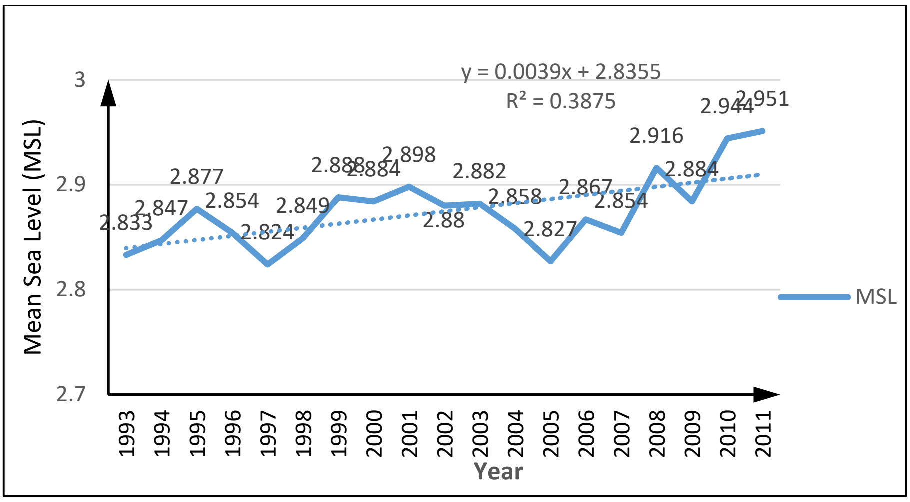


Figure 5: Graph of mean sea level versus years for Johor Bahru

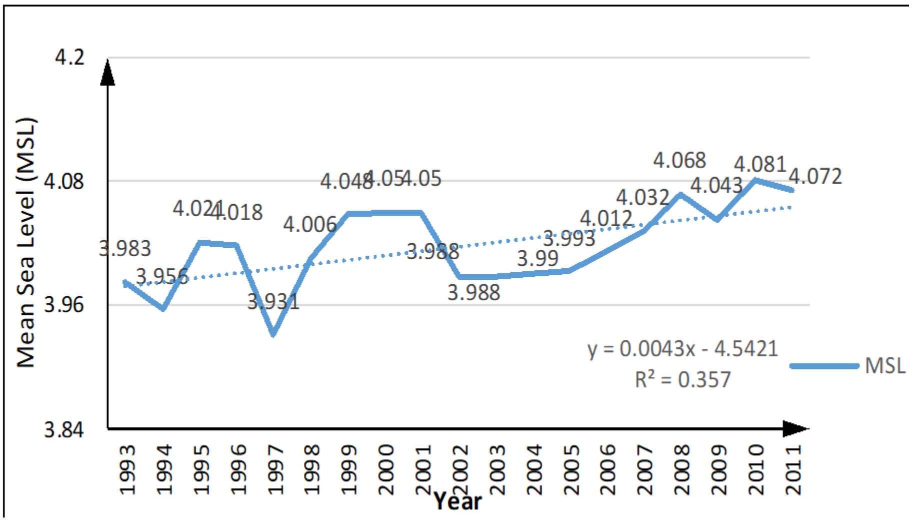


Figure 6: Graph of mean sea level versus years for Kukup

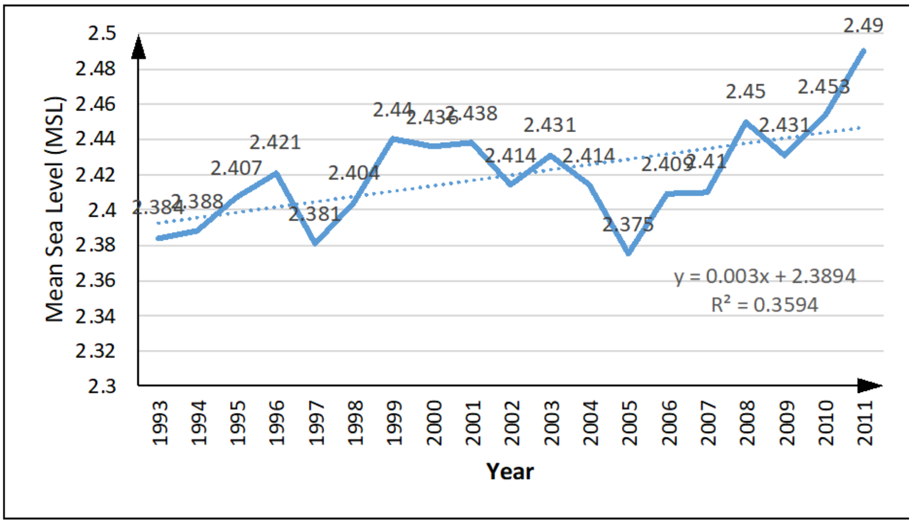


Figure 7: Graph of mean sea level versus years for Sedili

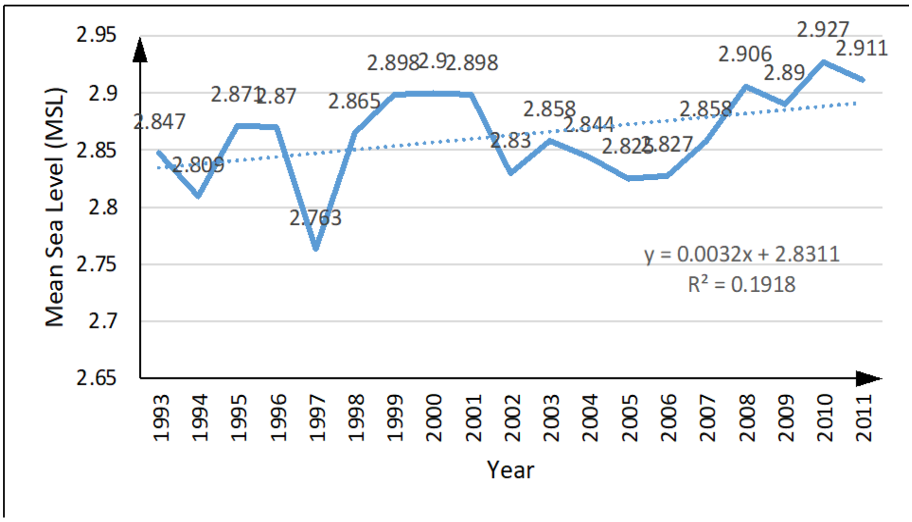


Figure 8: Graph of mean sea level versus years for Tanjung Kling

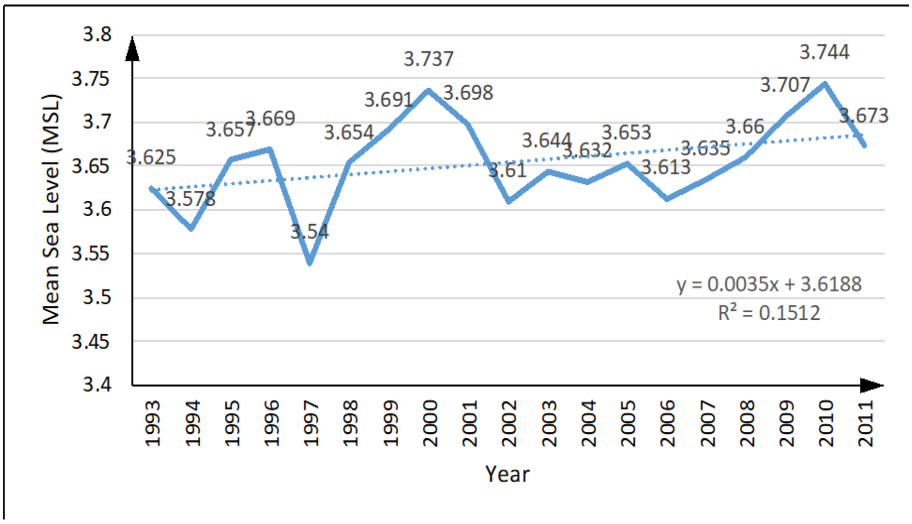


Figure 9: Graph of mean sea level versus years for Pelabuhan Klang

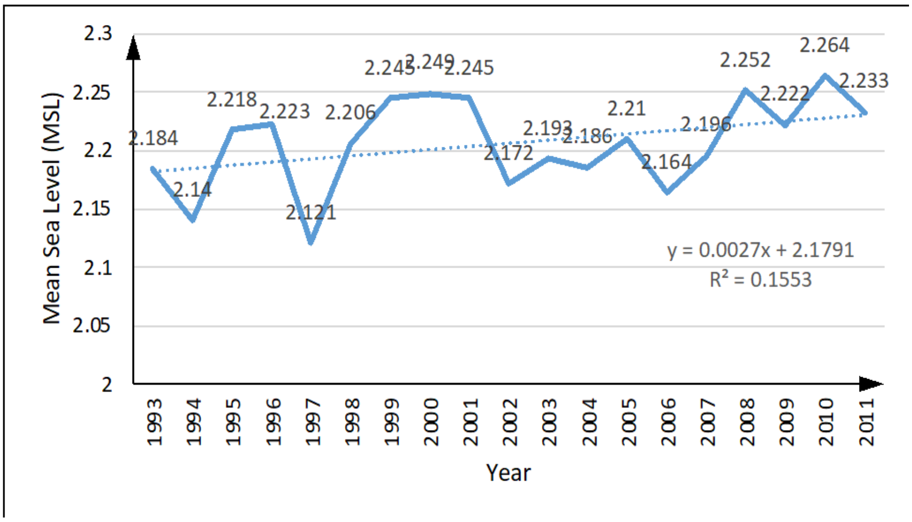


Figure 10: Graph of mean sea level versus years for Lumut

By referring to Figure 5 until Figure 10, it is clearly shown that the mean sea level related to the sea level rise is occurring along the Malacca strait that located on the west coast of Peninsular Malaysia, where the regression line indicates an increasing trend of the mean sea level over time, if the regression line is being extended, it will be showing the trend will continue increasing over time. The average mean sea level for Johor Bahru, Kukup, Sedili, Tanjung Kling, Pelabuhan Klang and Lumut are 2.875, 4.017, 2.420, 2.863, 3.654, 2.206 respectively. The average mean sea level for the six locations along the Malacca strait is 2.991, demonstrating the sea-level rise along the coast. The average data has been taken to generate graph to reduce the error for the data in each of the location along the Malacca strait.

Significant fluactuations in MSL data in 1997 until 2001, the relationship between mean sea level and tidal dynamic is a direct relationship whereby the increasing in MSL will increase tidal dynamic value. Since 1983, the Malaysian authorities have constructed a network of tidal stations across Sabah, Sarawak and Peninsular Malaysia [1]. The primary aim of developing a tidal network in Malaysia is to continuously observe tides. At least 19 years of data are necessary to develop an accurate tidal datum that takes all astronomical and meteorological factors into account at each tidal station. These include the establishment of a station's mean sea level (MSL) value, which mean the sea level is correlated to MSL and the data of MSL is relevant to be used as references of the trend in the tidal dynamics. There are formula that show correlation of MSL and sea level which is ‘X = Zo(t) + T(t) + S(t)’ where (Zo) is the mean sea level, (S) is meteorological component and (T) is tidal components. El Nino is a meteorological impact on tidal variations that is connected with the movement of the sea level, air pressure, and wind. Based on the Figure 11 to Figure 16, there are fluctuation in the graph and this problem would be discussed.

Between the years of 1997 to 2001 there are significant increase of the graph because of the El Nino and La Nina effect, these events happen between 1997 to 1998 and 1998 to 2001 respectively. The effect of El Nino climate phenomenon can be seen until 1998. Warming phenomenon of sea water is known as effect El Nino, but it also causes exceptional fluctuations in sea level. For example, a massive wave created by the storm that pounded the Pacific coast of California between 1982 and 1983 caused severe erosion in coastal regions [3]. This circumstance may result in large waves, which will have the impact of coastal erosion, inflicting damage and loss of property. Tropical Storm "Greg" made landfall on the northwest coast of Sabah State, Malaysia, on December 27, 1996, dumping torrential rains and triggering widespread flooding. According to a report from BERNAMA (Malaysia News Service), 170 fatalities were recorded, with more than 100 people still unaccounted for.

Significant fluactuated between 2005 to 2011, according to the Department of Irrigation and Drainage Malaysia, there are two kinds of rainfall that cause flooding, the first one is moderate intensity, long duration rainfall that covers a large region, and the second one is high intensity, localised rainfall. Additionally, flood data show that floods occur in a seasonal rhythm. Floods mostly impact the east coast and southern parts of Peninsular Malaysia, Sabah, and Sarawak during December and January, when the northeast monsoon is predominant. Flooding happens because of widespread extended heavy rainfall, which creates a high concentration of runoff that exceeds the capacity of streams and rivers. Numerous regions are often flooded. On the other side, the west coast of Peninsular Malaysia is most impacted from September to November, when convectional thunderstorms become common. These storms produce brief but heavy rainfall, severely overloading drainage systems and resulting in localised "flash" floods. According to [8]. Peninsular Malaysia was hit by a series of storm events caused by the Northeast Monsoon between 19-31 December 2006 and 12-17 January 2007, resulting in severe flooding in a number of states in the peninsula's lower half. The 2006 and 2007 events cost Malaysian states Negeri Sembilan, Melaka, Pahang, and Johor millions of dollars in lost income and property damage. The intensification of typhoons may result in an increase in maximum surges, wave height, and water depth, all of which contribute indirectly to the degree of sea level rise [13].

The average annual temperature has been increasing. Their analyses projected temperature increases of between 0.99 °C and 3.44 °C during the following century. Additionally, they observed an increasing trend in temperature for all of their stations over the last three decades, thus the research indicates climate change happen in Malaysia. In 2005, the wind direction was recorded at its highest velocity, owing to the influence of monsoons [7]. The Madden-Julian Oscillation (MJO) is the main component of the tropical atmosphere's intraseasonal (30–90 day) variability, this happens in around 2006 to 2007 where strong easterly winds near Java, linked with a Rossby wave-type reaction to the Madden-Julian Oscillation (MJO), prevented the northeasterlies from rotating counter-clockwise and forming the Borneo vortex [10].

3.2 Plaxis Simulation

In this simulation, load that applied on the embankment will be 2.22 kN/m^2. The embankment was built in 2 conditions, which is the original condition and present condition. The original condition represented the perfect original condition of the embankment when it was first built, while the present condition is the current condition of the embankment after several years. To indicate the failure of the structure in the embankment, a modification was made for the present condition of the embankment where the Young Modulus is being manipulated. Young Modulus for the original condition is set to be 1300 kN/m^2, while for the present condition, the Young Modulus decreased by half to weaken the strength of the embankment and show the present condition of the embankment. 650 kN/m^2 is the new Young Modulus for the silty clay on the embankment.

3.3 Total Displacement

In PLAXIS, the horizontal displacement and vertical displacement components after the current computation step are represented by the cumulative horizontal and vertical displacement components at all nodes, respectively. When the overall displacement is considered, it can be shown that the failure mechanism becomes more severe as the pore pressure distribution becomes more extreme.

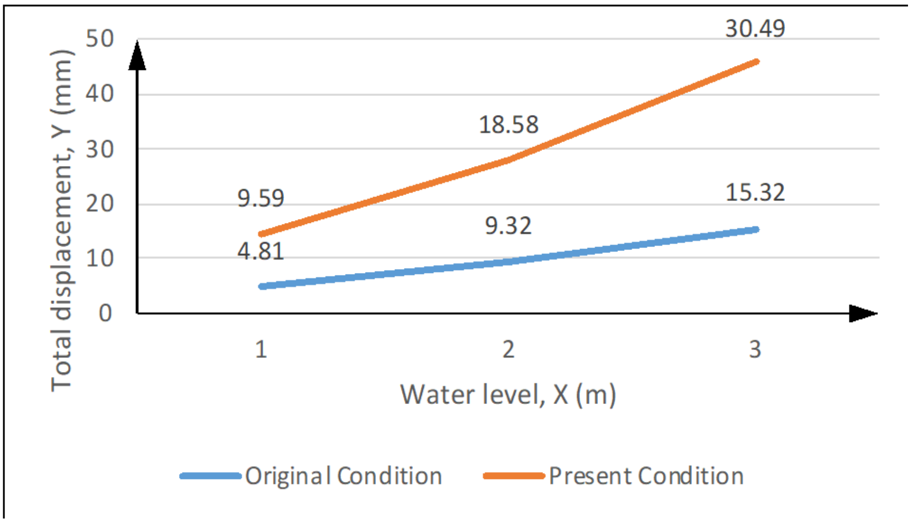


Figure 11: Graph of Water level vs. Total displacement

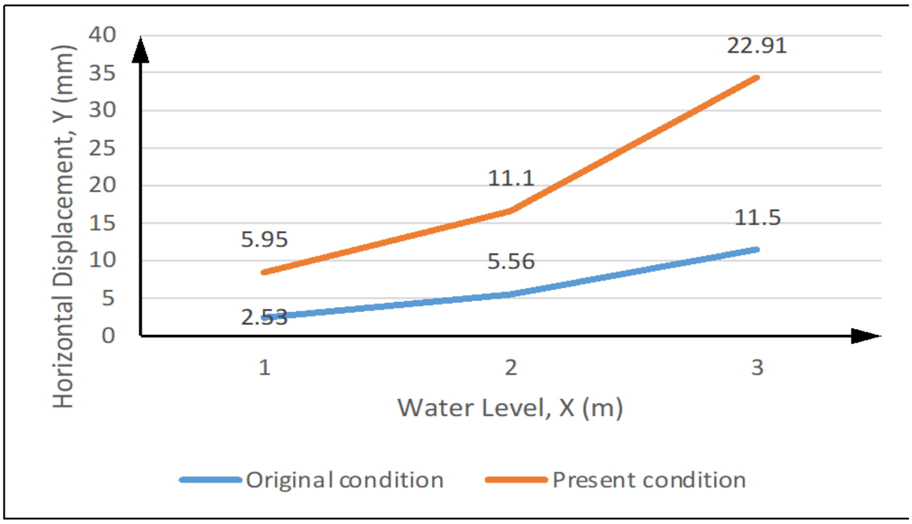


Figure 12: Graph of Water level vs. Horizontal displacement

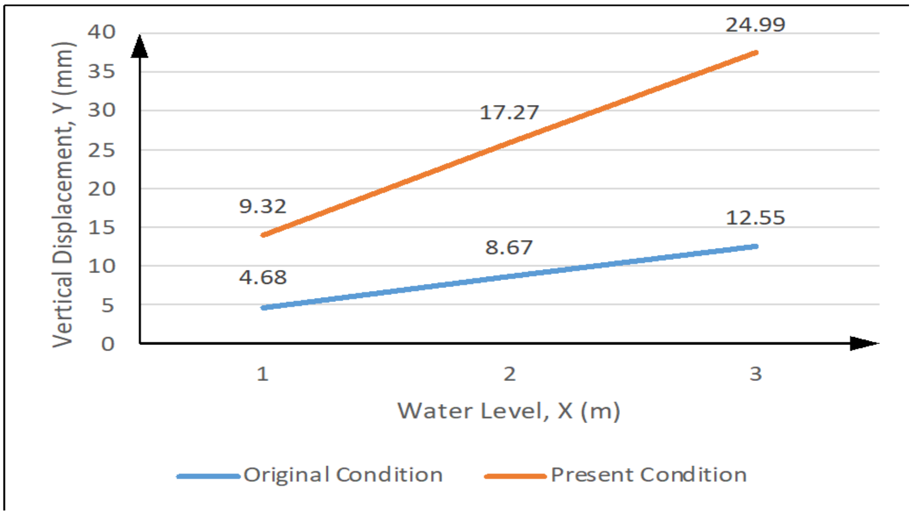


Figure 12: Graph of Water level vs. Vertical displacement

Figure 11 shows the water level vs. total displacement graph for the embankment that indicates the original and present condition of the embankment. The graph clearly shows that the total displacement of the original and present condition directly increases when the water level increases, as the water level will rise over time because of sea-level rise, which leads to failure and a more tremendous amount of displacement for the embankment. This is because the original embankment has a greater value of Young Modulus, which is 1300 kN/m^2 while the present condition of embankment has half of it, which is 650 kN/m^2, the low the value of Young Modulus, the less the strength of the soil. This is shown in the graph. For example, for 1m water level for the original condition, the total displacement is 4.81 mm, but the present condition with the value of lower Young Modulus shows the increase of the data by 9.59mm total displacement for 1m water level.

Figure 12 and Figure 13 shows the graph of water level vs horizontal and vertical displacement, the trend in increasing in displacement with water level, the main cause increased in displacement is the rising water level, the higher the water level, the higher the displacement will be. The present condition where the condition of the embankment is already severe where the embankment has weaken the strength, lead to the failure of the embankment which is displacement. This can be related to the climate change consequences, where rising sea level giving an impact to the embankments, where over the time, the water level would always be increasing continuously and displace the embankment.

3.4 Effective Stress

Effective stress can be defined as the tension that keeps particles together. Soils are held together by the combination of pore pressure and total stress.

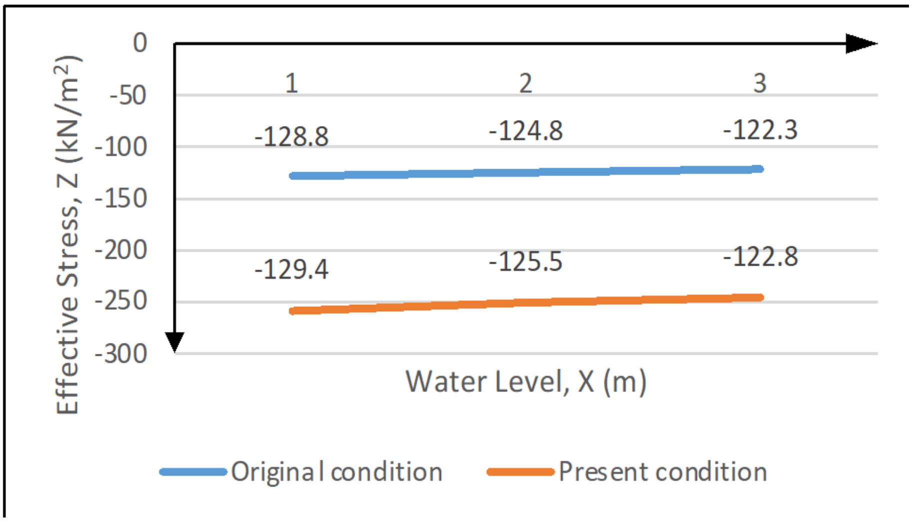


Figure 13: Graph of Water level vs. Effective stress

Due to the current state of silty clay, the effectiveness dropped with the increasing water level, from -129.4 kN/m^2 to -125.5 kN/m^2, and -122.8 kN/m^2 at 3 m water level. Increased pore pressure in soil reduces effective stresses by Ds' and the critical strength of the soil by Dt. The negative values indicate high tensile stresses acted on the embankment. Negative stresses indicate a state of partial saturation of soils.

The implications are that when with the increase in the effective stress of the soil, the rate of compression of soil also increases. This results in the settlement of the soil. If the water level keeps increasing by the effect of sea level rise, the condition of the embankment would become severe because more water is penetrating the soil.

3.5 Excess Pore Pressure

Excess pore pressure is calculated using PLAXIS modeling by determining the stress point in the embankment simulation, as the water level rises, the excess pore pressure increases as well. Increased water level might increase excess pore pressure because the material is saturated due to water seepage into the embankment body. For instance, at 1 m water level, the excess pore pressure of the original silty clay was 0.039 kN/m^2, but at 3 m water level, it was 0.180 kN/m^2. In addition, increased water levels might increase excess pore pressure because the material is saturated because of water seepage into the embankment body. Saturated material increases the extra pore pressure, particularly at the 3 m water level when the embankment is saturated by increasing water. Excess pore water pressure is the pore pressure more than a steady-state flow condition. If the sea water level keeps increasing, this will induce the excess pore pressure to increase. By time climate change which is rising sea level will continuously rising over the time, the embankment will have a low strength if this happens in future and potentially collapse.

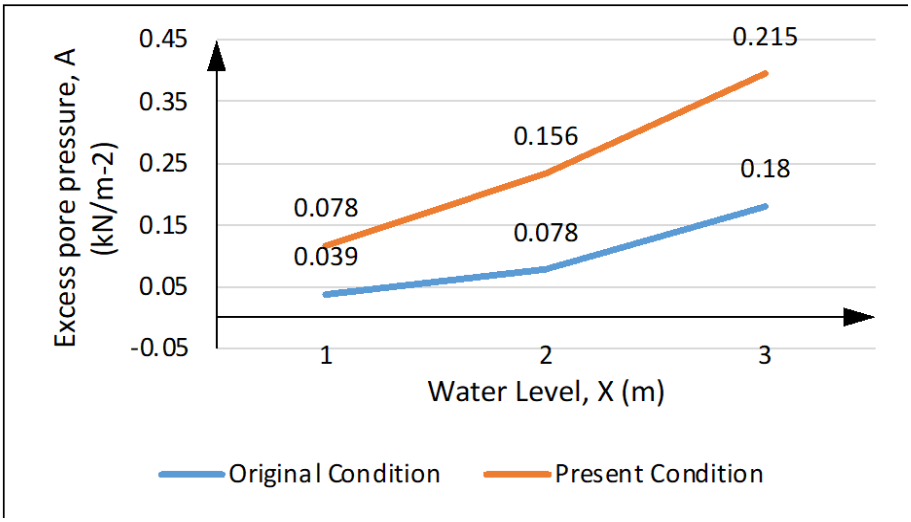


Figure 14: Graph of Water level vs. Excess pore pressure

From the graph in Figure 14, the value pattern of excess pore pressure for present condition is higher than original condition. For example, the value of excess pore pressure for 3 m present condition was 0.215 kN/m^2 while 0.180 kN/m^2 for original condition of silty clay. This indicated that the stability of embankment with getting severe over time. Rise in pore-water pressure reduces the shear strength of the soil.

3.6 Seepage

In PLAXIS, the total seepage discharge may be determined by creating a cross-section while viewing the groundwater flow graph. The higher the water level, the greater the seepage discharge. Increasing pore water pressure will lead to a reduction in stress, while decreasing pore water pressure will lead to an increasing in stress. When the stress increases, so that can increase the soil strength to against instability.

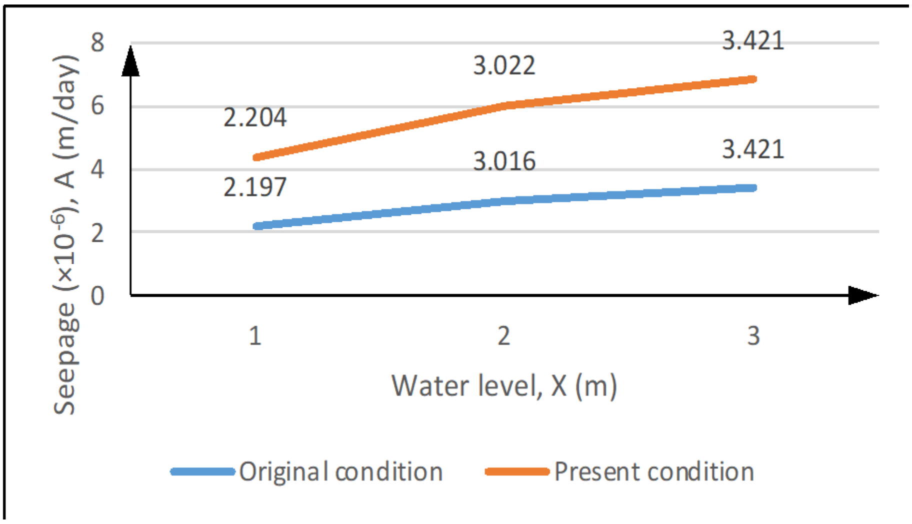


Figure 15: Graph of Water level vs. Seepage

A saturated slope that produces slides may exhibit indicators of an abnormal amount of sealing pressure. Seepage that is not maintained may erode the soil and result in structural collapse. Seepage may collapse slope by increasing pressures inside the soil pores or flooding the slope. Figure 15 shows a Graph of Water level vs. seepage. The graph shows that the higher the water level, the higher the seepage. For example, for the original condition of the embankment, the seepage in 1m water level is

2.197×10^{-6}, whereas for 2 m, it is 3.016×10^{-6}. This also happens in the present condition of the embankment. The more the seepage, the severe the condition of the embankment.

3.7 Analysis on area of Senggarang Coastal area from Google Earth and Climate Central.

Based on Figure 16, which depicts the condition of the coastal area along the Senggarang area in 1984, it can be seen that the area of the coastal is still in good condition, with the area remaining large and free of soil erosion. However, over the previous 36 years, it has been clearly shown in Figure 17 that a portion of the region along the shore has already been degraded. According to the computation generated by Google Earth, the eroded region covers an area of about 55410.88 m^2. This indicates that the coastal region is being degraded as a result of the increasing sea level's effect and climate change.

In 2030, according to Climate Central's predictions, the land would be below the 10-year flood level, as seen in Figure 17 Climate Central provides thousands of local events and aesthetically compelling visuals that bring climate change to life and explain what can be done to prevent it via the use of science, big data, and technology innovation. According to the projection shown in Figure 18, Senggarang is anticipated to be a place where the flood level will be lower and where there will be a higher hazard of rising sea level rise than the rest of the province.

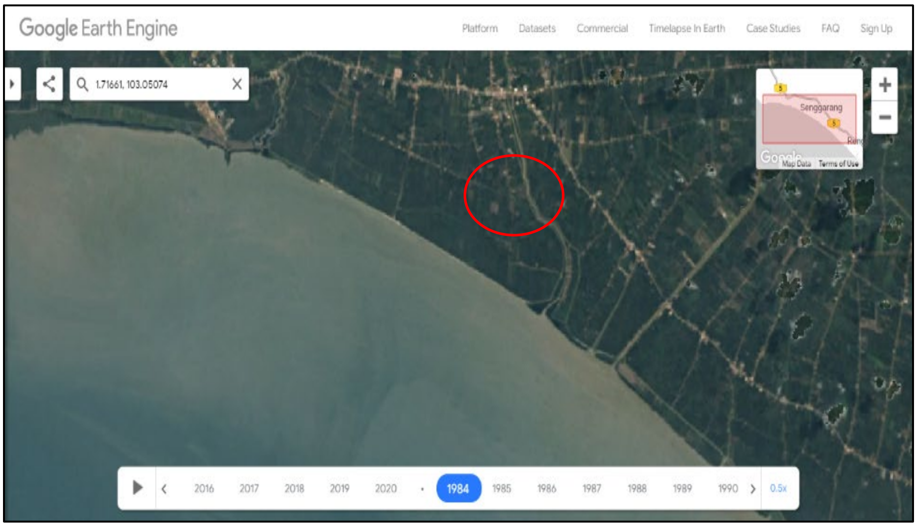
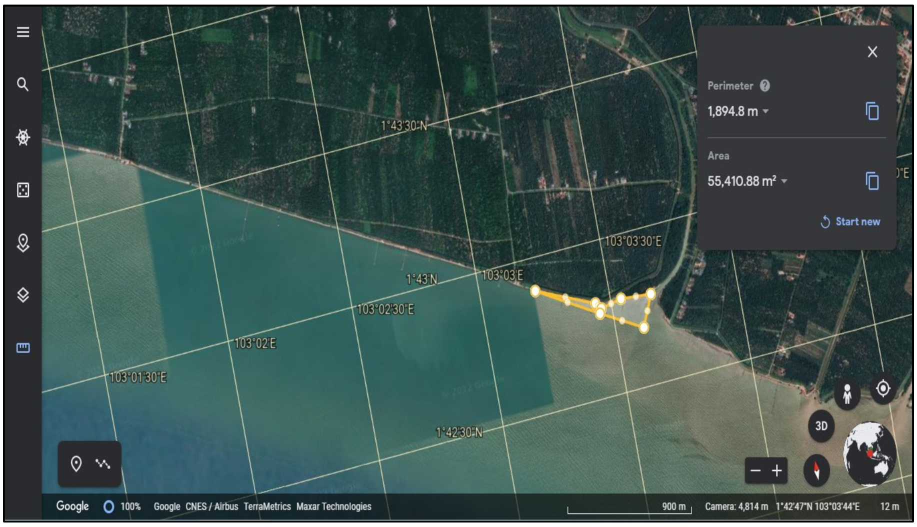


Figure 16: Senggarang area in 1984 (Google Earth)



Perimeter
1,894.8 m

Area
55,410.88 m²

Figure 17: Senggarang area in 2020 (Google Earth)

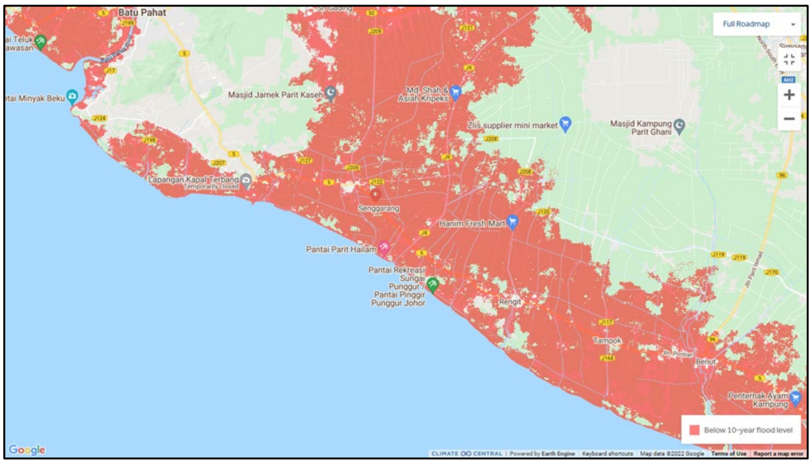


Figure 18: Senggarang area projection below 10-year flood level in 2030 (Climate Central)

4. Conclusions

This research achieved all of its objectives. Rising sea levels due to climate change. The numerical simulation of Senggarang embankment with silty clay soil worked well. Both of the simulation were successfully analysed in term of displacement, effective stresses, excess pore pressure and discharge of seepage. The first objective, to examine the tidal dynamics at Senggarang Coastal Embankment (SCE) in the past decade in relation to climate change, was accomplished. On the graph, a regression line depicts the effect of climate change on sea-level rise over time, which eventually failed the embankment. The 18-year average sea-level increase along the Malacca Strait is evidently clear.

The second objective is to design a Failure Risk Assessment tool for Senggarang Coastal Embankment (SCE) utilising Plaxis software. This simulation tests the embankment's stability and strength. 3 m of seawater were simulated using Plaxis software. Then it was reached using the assumed original and current embankment condition. The greater the water level, the more seepage. The smaller the flow of seepage, the less stable the embankment. The state of the embankment will worsen as the sea level rises due to climate change. This study provided many suggestions to improve the quality of similar studies and future research, including laboratory testing to determine real soil qualities like permeability and seepage. On-site monitoring of tide patterns and their impact on seepage.

Acknowledgement

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