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RIVERBANK PROTECTION STRUCTURE FAILURE FACTORS AND REMEDIAL APPROACH: A CASE STUDY IN KELANTAN MALAYSIA

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Abstract

Numerous structural mitigation measures have been implemented to ensure the sustainability of socio-environmental systems. Riverbank erosion can be avoided through the installation of reinforced walls, groynes, and sheer piles, among other measures. However, these structures sometimes fail to protect riverbanks from collapsing due to various factors, including environmental and anthropogenic influences. Therefore, this study aims to identify the factors contributing to the failure of riverbank protection structures and determine remedial approaches to enhance them. The study utilized a combination of site visits, document analysis, and interviews with riverbank protection structure engineers and contractors to gather the necessary information to achieve study objectives. The study found that geomorphology; hydraulics; and unstable sheet pile construction were the factors to the riverbank failure. Besides, study also recommend the suitable remedial approach in terms of design; construction and maintenance to build a stable riverbank protection structure (rock embankment). The findings of this study can contribute to the development of more effective and sustainable riverbank protection measures, which are essential to protect vulnerable communities and ecosystems from the impacts of environmental hazards. The study's results can guide policymakers, engineers, and other stakeholders involved in riverbank protection to better understand the factors that contribute to structure failure and how to mitigate these risks. It can also contribute to the advancement of knowledge in the field of riverbank protection, specifically in identifying the most effective mitigation strategies.

***Keywords**:* Environmental Hazards, Riverbank Collapse, Sustainable Development and River Remedial Structure

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INTRODUCTION

Rivers is very important to play the role to sustain life and the environment (See Too et al., 2023; Saad et al., 2023). Water resources are extensively used for domestic, agricultural, and industrial purposes. They also support recreational activities and provide habitat for aquatic plants and animals (Shu et al., 2019; Mustaffa et al., 2023). However, river bank is very fragile to eroded by the hydraulic action and this may lead to the loss of land, property, and infrastructure (Hague and Zaman, 1989). In Malaysia, riverbank erosion is a major environmental problem that affects the country's economy and the community’s livelihood (Azid et al., 2015; See Too et al., 2023). Force of flowing in hydrology system cause the erosion of the riverbed and banks (Avendario and Lopez, 2013; Toriman et al., 2015). Erosion process in massive rivers such as Kelantan River can be complex and involve various factors, including the type of sediment, the flow rate, river morphology, the structural measures and the bank vegetation (Jaafar et al., 2010; See Too et al., 2022).

Hydraulic action and structural factors make up the bulk of riverbank erosion factors. Through hydraulic action, the force of flowing water can pressurise sediment out of the riverbed and the banks (Avendario and Lopez, 2013; Abdul Maulud et al., 2021). Massive rivers can experience widespread erosion, which can have a significant impact on the morphology and course of the river (Dekaraja and Mahanta, 2020). In addition to creating landforms like meanders and deltas, erosion can also deposit sediment in floodplains and canyons over time (Rasheduzzaman et al., 2007).

One specific case of a riverbank protection structure failing occurred in the Philippines' town of Molo in 2011 (Dekaraja and Mahanta, 2020). The town was located alongside the Jalaur River, which was vulnerable to erosion and flooding during periods of intense rainfall. In response, the town was shielded from erosion and flooding by a concrete dike that the local government had built along the riverbank. Numerous factors, including subpar construction, insufficient maintenance, and the overwhelming force of the floodwaters, were blamed for the protection structure's failure (Dekaraja and Mahanta, 2020). The town of Molo suffered severe repercussions from the collapse of the riverbank protection structure, including the loss of residences, commercial buildings, and agricultural land. The local government and international aid agencies worked to repair and reinforce the riverbank protection structure and enhance disaster preparedness measures in response to the disaster (Cavaille et al., 2013). This illustration demonstrates the significance of correctly building, maintaining, and monitoring riverbank protection structures as well as the requirement for efficient disaster preparedness and response measures in regions vulnerable to flooding and erosion (Berkovich et al., 2019).

In 2014, another instance of riverbank protection structure failing in Kuala Krai, Malaysia (Berita Harian, 2015). One of the worst floods to ever affect the area hit the district, severely damaging buildings, infrastructure, and agricultural land. The existing riverbank protection structures were destroyed as a result of the floodwaters' severe erosion along the riverbank. In Kuala Krai, the structures used to protect the riverbanks were constructed from a mix of gabion baskets, concrete walls, and vegetation. However, the riverbank suffered severe erosion and buildings nearby could not withstand the force of the floodwaters. The failure of the riverbank protection structures in Kuala Krai serves as a reminder of the significance of proper riverbank protection structure design, construction, and maintenance in Malaysia.

Since river bank failure is a significant issue, it brings numerous negative impacts to the local community and social activities around the affected area. Therefore, this article holds significant importance in investigating the factors and suggesting approaches to enhance the river bank structure. This study may also be serving as a reference point to the local authorities and decision-makers, before they take action to improve the river bank structure.

LITERATURE REVIEW

River Bank Failure in Malaysia

In Malaysia Sungai Batu Pahat river, there was a case of sheer pile failure due to riverbank erosion. The urban river frequently floods and erodes because it is located there. Along the riverbank, a concrete dike with a sheer pile foundation was built to reduce the effects of erosion. However, the sheer pile foundation of the dike failed during a period of intense rain in 2017, causing significant damage and riverbank erosion. A number of factors, such as soil instability, scour, and wave action, were blamed for the failure. Riverbank erosion is significantly influenced by poor construction methods (Jun Yang, 2023). Common instances of subpar construction include the use of inferior materials, improper installation, insufficient quality assurance, and inadequate consideration of hydrological factors (Knut et al., 2020). The failure of riverbank protection structures can be significantly impacted by inadequate maintenance (Hadayani et al., 2023). The effectiveness of structures and their ability to withstand the forces of erosion and water flow over time depend on routine maintenance. Inadequate maintenance can lead to a number of factors, including vegetation growth, soil erosion, wear and tear, and weathering.

Although soil erosion is a natural process that happens over time, human activities like changing land use, deforestation, and improper water resource management can speed up the process (Jun Yang, 2023). Soil erosion, if unchecked, can damage riverbank protection structures' structural integrity and result in failure. Inadequate maintenance leading to riverbank protection structure failure all over the world, including in Malaysia (Berita Harian, 2015). For instance, due to inadequate maintenance, riverbank protection structures have failed numerous times in the Kuala Krai district of Kelantan, Malaysia. A section of the district's riverbank protection structure collapsed in 2014, resulting in flooding in the nearby areas (Berita Harian, 2015). Insufficient maintenance, which had caused soil erosion and the building's gradual weakening, was identified as the cause of the failure.

RESEARCH METHODOLOGY

The experts in riverbank protection, including construction engineers, employees of the Department of Irrigation and Drainage Malaysia (DID), and contractors working on the riverbank stabilisation project, were consulted as part of this study's qualitative approach to gather crucial and pertinent data. After the government decided to rebuild and stabilise the riverbank, the interview sessions were held in person. This strategy was used to make sure that the study got information from the right people who were knowledgeable and experienced in protecting and building riverbanks. In addition, the study made thorough site visits starting from the project's inception to gather historical information and gauge the sizes of structural cracks. The social and environmental effects of the riverbank failure could be seen firsthand during these site visits. In addition, a document analysis was done to extract specific data from the DID. In order to do this, it was necessary to review pertinent documents like engineering reports, design plans, and project specifications.

The study was able to gain insightful knowledge and a thorough understanding of the riverbank protection measures implemented by the DID by examining these documents. The study aimed to gain a thorough and trustworthy understanding of the riverbank protection approach and the ongoing construction by utilising this combination of qualitative data gathering techniques, including interviews, site visits, and document analysis. The inclusion of experts, first-hand observations, and careful document analysis ensured the gathering of pertinent and useful data for the study's goals.

RESEARCH LOCATION

Kelantan is located in East Coast of Malaysia. More extreme rainfall events were experienced during the monsoon season, which had an impact on the morphology and community settlements along the Kelantan River. The Kelantan River's morphology features may significantly contribute to riverbank failure. In addition, the lower stream of Kelantan River was vulnerable to river bank failure due to its located in the flood-prone area (See Too et al., 2022). Kelantan River also has high capacity for transporting sediment and its meandering and braided channels, the riverbanks may experience significant erosion. The study area is located across from the Kelantan River's meander as it passes through Pasir Mas. Prior to the riverbank failure incident in February 2021, Pasir Mas had not experienced a serious major riverbank failure despite experiencing heavy rain and flooding every year during the monsoon.

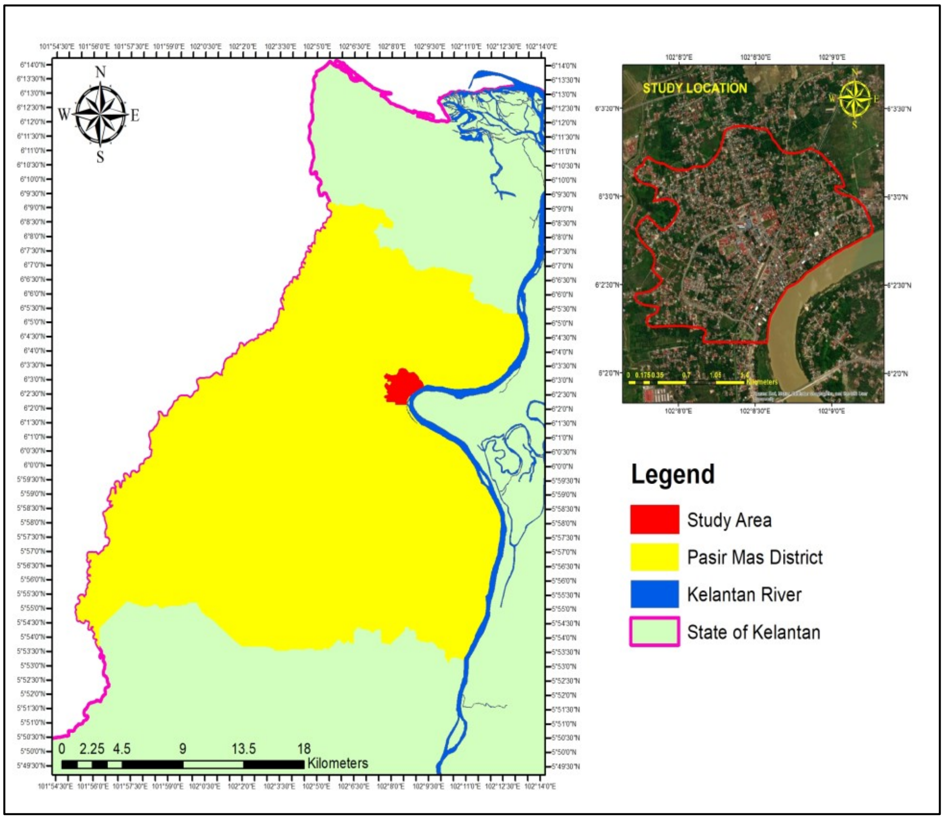

Figure 1: Research Location

RESULT AND DISCUSSION

Chronology of riverbank failure at research location

The local community in Kg. Pohon Celagi, Kelantan, has been significantly impacted by the riverbank failure that started on February 17, 2021 (Table 1.). They were surprised by the incident, which happened around 7 am, when the riverbank suddenly collapsed vertically. Authorities desperately warned residents to evacuate to safer areas has resulted of this sudden failure. Two vehicles were engulfed and carried away by the crumbling soil, demonstrating the severity of the collapse and underscoring the potential dangers associated with riverbank failures.

Table 1: Structures Cracking Data **(Feb 2023)**

Date	**18**	**19**	**20**		**21**	**22**	**23**	**24**	**25**	**26**	**27**
Day	**Thu**	**Fri**	**Sat**	**Sun**	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Time	**5:00 pm**	**4:00 pm**	**10:00 am**	**3:00 pm**	**10:30 am**	**9:00 am**	**9:00 am**	**10:00 am**	**10:00 am**	**12:00 pm**	**10:00 am**
WL (m)	1.73	1.83	1.66	1.79	1.60	1.55	1.50	1.46	1.50	1.52	1.59
No. 1	7	7	7	7	7	9	9	10	11	6	7
No. 2	7	8	10	17	24	29	35	41	N/A	50	52
No. 3	9	12	24	31	35	42	48	53	N/A	68	70
No. 4	6	7	7	8	5	5	5	5	N/A	5	5
No. 5	105	120	155	184	220	223	225	227	260	230	235
No. 6	27	27	28	28	28	33	33	38	40	33	43
No. 7	28	28	29	29	46	50	51	52	70	75	70
No. 8	10	N/A	N/A	N/A	12	N/A	15	17	N/A	22	N/A
No. 9	8	8	8	8	8	8	8	8	8	7	5
No. 10	12	12	12	12	12	12	12	12	12	6	N/A
No. 11	2	2	2	2	2	2	2	2	N/A	N/A	N/A
No. 12	568	568	568	568	573	575	571	571	N/A	N/A	N/A
No. 13	-	-	-	20	20	20	20	28	28	21	25
No. 14	-	-	-	10	N/A	12	12	12	12	10	N/A
No. 15	-	-	-	32	N/A	39	40	43	N/A	46	N/A
No. 16	-	-	-	58	65	71	78	80	N/A	97	N/A
No. 17	-	-	-	10	15	34	35	50	60	40	N/A
No. 18	-	-	-	-	14	28	24	30	35	52	N/A
No. 19	-	-	-	-	-	9	9	9	10	15	N/A
No. 20	-	-	-	-	-	10	23	35	55	85	N/A
No. 21	-	-	-	-	-	15	20	30	N/A	70	N/A
No. 22	-	-	-	-	-	13	16	22	N/A	20	N/A
No. 23	-	-	-	-	-	-	-	13	N/A	16	16
No. 24	-	-	-	-	-	-	-	45	45	45	45
No. 25	-	-	-	-	-	-	-	75	75	165	165
No. 26	-	-	-	-	-	-	-	50	50	51	51
No. 27	-	-	-	-	-	-	-	52	52	52	52
No. 28	-	-	-	-	-	-	-	-	22	30	N/A
No. 29	-	-	-	-	-	-	-	-	-	19	N/A
No. 30	-	-	-	-	-	-	-	-	-	71	120
No. 31	-	-	-	-	-	-	-	-	-	-	40
No. 32	-	-	-	-	-	-	-	-	-	-	24
No. 33	-	-	-	-	-	-	-	-	-	-	12
No. 34	-	-	-	-	-	-	-	-	-	-	10
No. 35	-	-	-	-	-	-	-	-	-	-	9
No. 36	-	-	-	-	-	-	-	-	-	-	10
No. 37	-	-	-	-	-	-	-	-	-	-	25

The incident in Kg. Pohon Celagi serves as a reminder of the unpredictable nature of riverbank failures and their capability to cause significant harm to both the community and its priceless assets. This study evaluated the severity of the harm caused to various structures within the impacted area in response to the incident. In order to understand the effects of the failure, the study included analyses of buildings, roads, sheer piles, and houses. The study's findings showed that there were 37 active cracking points, with both the size and number of cracks progressively growing larger as time went on (Table 1.).

This information not only highlights how persistent the riverbank failure is, but it also shows that even after several days have passed, things are only getting worse. The worrying expansion of the cracking points is a glaring indication that the soil's instability is still a major cause for concern. The environment is extremely unstable due to the soil's ongoing slight movements, making the area dangerous for both the nearby community and the existing structures.

The riverbank failure factors

Geomorphology

Geomorphology, hydraulics, and shaky sheet pile construction are the causes of riverbank failure in the study area. Rivers are dynamic systems that are constantly interacting with their surroundings. Erosion, sedimentation, and channel dynamics are all significantly influenced by a river's geomorphological features (Mohd Ekhwan, 2007). This study explores the various ways that geomorphology affects riverbank stability and emphasises the significance of taking these factors into account during design and implementation. More energy is exerted on riverbanks by higher flow rates, which can result in more erosion and possible instability (Duró et al., 2018, 2019, 2020). Additionally, the distribution of flow forces along the banks can be influenced by the width and depth of the river channel, which can affect erosion patterns and the efficacy of protective measures (Duró et al., 2020). On the other hand, the movement of sediment within a river system has a direct impact on the stability of riverbank protection structures (Duró et al., 2018). Meanders, bends, and point bars are examples of geomorphological features that significantly contribute to bank erosion (Liu et al., 2017). On the other hand, according to Duró et al. (2018), the stability of riverbank protection structures is directly impacted by the movement of sediment within a river system.

This migration is also significantly influenced by geomorphology, which presents difficulties for riverbank protection structures. Existing structures may be destroyed or avoided as a river meander and changes its course, rendering them useless (Hasanuzzaman et al., 2022). It is crucial to take channel migration into account during the design process and create safety protocols that take long-term changes in the river course into account. The geotechnical characteristics of riverbanks, such as the soil composition, compaction, and stability, are also influenced by geomorphology. The stability of riverbanks depends on vegetation (See Too et al., 2023). The location and type of vegetation along riverbanks are influenced by geomorphology, which in turn affects erosion rates and slope stability. By providing root systems that bind the soil, dissipating hydraulic forces, and lowering erosion rates, riparian vegetation, such as grasses, shrubs, and trees, can improve bank stability. When designing protection measures, geomorphological assessments should take into account the presence and characteristics of vegetation.

River hydraulic

Understanding and predicting the stability of riverbank protection structures requires an understanding of river hydraulics, the behaviour and characteristics of flowing water (Knut, 2020). The hydraulic forces generated by river flow have a direct impact on the processes of erosion, scouring, and sedimentation along riverbanks (Glidas et al., 2019). One important hydraulic factor that affects the stability of riverbank protection structures is flow velocity. The amount of force and energy applied to the riverbanks depends on the river's flow velocity (Jun Yang, 2023). Huge erosion can result from faster flow rates, which can also make protection structures less stable. The importance of determining and controlling flow velocities near protection structures is highlighted by the fact that the erosive power of water is directly proportional to the square of the flow velocity (Glidas et al., 2019).

The Kelantan River is a huge river stream with dynamic morphology activities that may be influenced by human activity or natural forces. Due to its location downstream in the catchment, this river stream is extremely vulnerable. For instance, the collapse of the riverbank at Kg. Pasir Parit occurred during the monsoon season. More than 20 people lost their homes in the disaster, and the riverbank collapsed, destroying their homes and other property (See Too et al., 2022). The water level is between 1.46 and 1.83 metres during the river bank failure happened in the research location. The water velocity during the monsoon season may cause bank erosion and collapse when the soil was loose due to hydraulic activity.

Sediment transport within the river system is also influenced by hydraulic factors, which in turn affects the stability of defence structures (Glidas et al., 2019). The stability of riverbanks may be impacted by sediment particles carried by the flow if they deposit along the banks or cause scouring (Kamarudin et al., 2017). Excessive sedimentation close to the banks can put more strain on the defences, which could cause instability. Designing protection measures that take sediment dynamics into account and reduce associated risks requires an understanding of the sediment transport dynamics, including sediment load, transport capacity, and deposition patterns (Kamarudin et al., 2017). Human activities can also have a significant impact on river hydraulic factors and, as a result, the stability of riverbank protection structures. Examples include flow regulation and channel modifications (See Too et al., 2022). The natural flow characteristics, such as flow velocity, flow distribution, and sediment transport, are changed by dams, levees, or channel straightening. Increased erosion rates or altered patterns of sediment deposition are just two examples of how these modifications may have unintended effects on the stability of protective structures. To reduce potential risks and guarantee the long-term stability of protection measures, careful consideration of the hydraulic implications of any human interventions is required.

Unstable sheer pile construction

Riverbank protection frequently involves the use of sheer pile construction. To provide stability and stop erosion, it entails driving vertical or slanted piles into the ground along the riverbank. However, because it was built in the 1980s, the sheer pile construction at the research site is not properly planned, executed, or maintained (DID, 2022). This may cause instability and reduce the protection structure's effectiveness. This study demonstrates the significance of proper design and implementation, such as in Kg. Pohon Celagi, Kelantan, unstable sheer pile construction can affect the stability of riverbank protection structures. The stability of sheer piles and the overall efficiency of riverbank protection structures depend greatly on their design. The piles might not be able to withstand the hydraulic forces and other loads acting on them if they are improperly designed. When the structures were not properly managed or build, it may cause the protection structure to become unstable, settle, or even fail. To ensure stability, sheer pile installation must be done carefully. The performance of the piles and the overall stability of the protection structure can be impacted by variations in soil properties like cohesion, permeability, and bearing capacity.

Sheer piles may deteriorate over time as a result of a number of factors, including corrosion, material deterioration, or damage from outside forces.

Remedial Approach

In order to stop erosion, preserve land, and preserve infrastructure along riverbanks, riverbank protection structures are crucial. But over time, these structures may deteriorate or lose their effectiveness as a result of a variety of things, including natural processes, hydraulic forces, or poor design. By using an appropriate remedial strategy, riverbank protection structures' stability and efficiency can be improved (refer Figure 2).

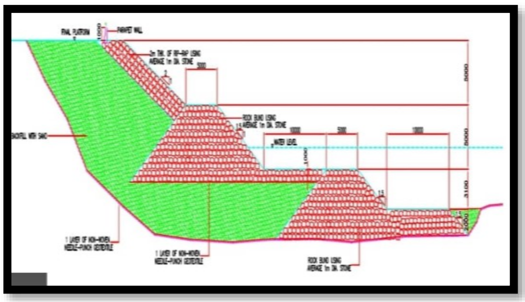

Figure 2: Rock Embankment Approach
(_Malaysia Department of Irrigation, 2021_)

The common remedial methods that can be used to fix problems with existing structures are examined in this article. The rock embankment that the Malaysian Department of Drainage and Irrigation (DID) built is quite stable and effective in preventing bank erosion, according to the study that was conducted.

Design

The Kelantan River's riprap failure was classified by the National Water Research Institute of Malaysia (NAHRIM) as a sideslope failure (refer Figure 3). Instability or failure of a sloping landmass or embankment is referred to as a "sideslope failure," and it is typically characterised by the movement or sliding of soil, rock, or other materials along a sloping surface. It is a kind of slope failure that can happen on both naturally occurring slopes and slopes that have been engineered, like levees, retaining walls, or highway embankments. Additionally, debris flow was the specific cause of side slope failure in the research location. Heavy rainfall frequently results in debris flows, which is particularly important given Kelantan's monsoon season. High rainfall levels in the area during this time of year can cause increased runoff and the possibility of debris flows. The stability of the riverbanks is significantly at risk of these debris flows, which can also contribute to riverbank erosion.

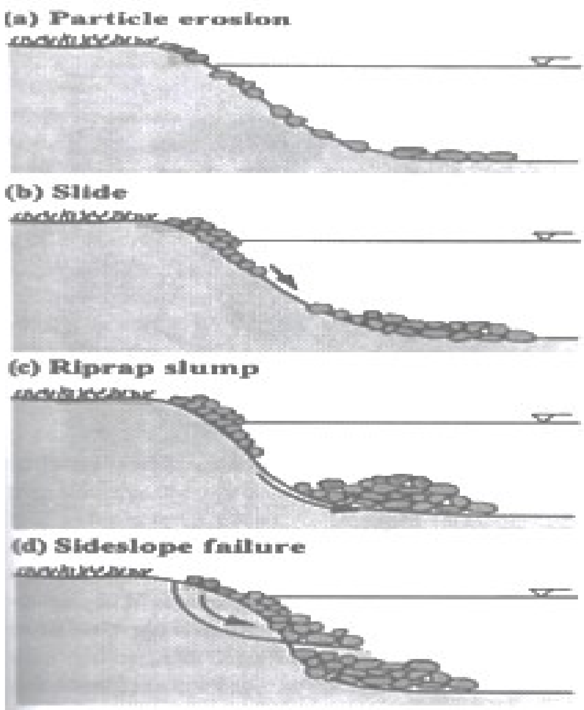

Figure 3: The Riprap Failures
(Julien, 2002)

To ensure the effectiveness of a rock embankment approach for protecting riverbanks from failure, several important factors and procedures must be considered. This study was carried out that soil characteristics, slope geometry, hydraulic conditions, erosive patterns and many more can be potential mechanisms for riverbank failure. The embankment design is created based on the site evaluation, geotechnical investigation, and hydraulic analysis. This involves figuring out the proper geometry, such as the setback distances, slope angle, and embankment height.

Construction

To make sure that the embankment is built in accordance with the design specifications, proper quality control procedures should be put in place during the construction phase. To achieve the desired stability and performance, construction methods like proper compaction, layering, and interlocking of the rock should be used. The site must be ready before construction can begin. In order to do this, the area must be cleared of all vegetation, any structures or debris must be removed, and the riverbank must be excavated to the necessary depth and slope. The stability of the embankment depends on its foundation. To achieve the needed bearing capacity, the foundation soil must be compacted. Additional precautions, such as soil stabilisation techniques, may be required if the foundation soil is fragile or unstable. Beginning at the bottom and gradually working their way up to the desired embankment height, the rocks are arranged in layers. To achieve the necessary stability, each layer is carefully positioned and compacted (refer Figure 4).

Figure 4: The Construction Progress

The rocks' mutual interlocking contributes to the stability of the structure. After the primary embankment construction is finished, the surface might be finished to add more security and appeal. To further increase the embankment's erosion resistance, this may entail adding a layer of smaller rocks or using geotextiles or erosion control blankets.

Maintenance
It's crucial to maintain the rock embankment that serves as the finished riverbank protection structure. To find and fix any potential problems or degradation, routine inspections, monitoring, and maintenance activities should be performed. Erosion control measures should be replaced or repaired right away if they become damaged. This might entail fixing erosion-related issues, stabilising troublesome areas, or, if necessary, adding more rock to the embankment to strengthen it. When performing repairs and maintenance, it is important to use the right construction methods and supplies to ensure the embankment's durability and efficacy. To stop additional damage and protect the lives and properties of those who live close to the riverbank, immediate action and extensive mitigation measures are required (See Too, 2023). Even after the installation of protection structures, geomorphological factors still affect the stability of riverbanks (Kamarudin et al., 2017). Continuous monitoring is essential for determining any changes or potential risks, as well as for understanding how the system responds to the implemented measures. Establishing a regular maintenance schedule and allocating funds for ongoing monitoring and maintenance efforts are also crucial. For reference and evaluation purposes in the future, it is crucial to keep thorough records of maintenance activities, inspections, repairs, and monitoring results. This documentation guides in monitoring the performance of the embankment over time, spotting patterns or trends, and directing decisions regarding future maintenance and management.
Determined by river hydraulics, the stability of riverbank protection structures is essential (Bruce and Ian, 2020). When developing and putting into practise protection measures, it is important to carefully consider variables like flow velocity, flow distribution, flow patterns, and turbulence, sediment transport, bank erosion, and the effects of human interventions. The stability of riverbank protection structures can be significantly impacted by unstable sheer pile construction (Ahmad, 2020). The potential instability of the piles and the entire structure is caused by inadequate pile design, improper installation methods, inadequate maintenance, hydraulic factors, soil conditions, and a lack of long-term monitoring and maintenance. To increase stability and prevent riverbank collapse, proper sheer pile construction must be designed, built, and maintained.

CONCLUSION
In summary, develop flood risk mapping and conduct flood risk index assessment in Kelantan floodplain is vital for reducing flood risk. It enables the identification of high-risk areas, informs land-use planning and infrastructure development, improves emergency preparedness and response, raises community awareness,

and facilitates the implementation of effective flood mitigation and adaptation strategies. By utilizing this study, Kelantan can enhance its resilience to floods and minimize the potential damage and loss associated with future flood events.

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DISCLOSURE STATEMENT
Following international publication policy and our ethical obligation as a researcher, we report that we have no conflict of interest.

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