A Review of Embankment Design on Artificial Islands by Dredge Material to Mitigate Flooding

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Received: 16 August 2024 | Revised: 4 October 2024, 8 October 2024, and 25 November 2024 | Accepted: 27 November 2024

 DOI: https://doi.org/10.48084/etasr.8758

ABSTRACT

Sedimentation in Lake Tempe, South Sulawesi, Indonesia, has led to significant reductions in the water storage capacity, necessitating dredging efforts and the reuse of Dredged Material (DM) for artificial island construction. This study focuses on designing stable embankments for these islands, which face heightened risks of failure due to the use of low-quality backfill materials and the extreme hydrological conditions. The objective is to determine the required embankment height and assess the effectiveness of geosynthetics and bamboo piles in enhancing slope stability. A comprehensive approach was employed, combining hydrological and geotechnical analyses. The hydrological analysis, based on the 20-year (Q_{20}) and 50-year (Q_{50}) return periods, determined embankment heights of 8.36 meters and 9.2 meters, respectively. The geotechnical analysis using slope stability models revealed that geosynthetic reinforcement significantly outperformed bamboo piles, achieving safety factors well above the critical threshold (1.25) compared to the sub-threshold values for the bamboo piles. These findings underscore the critical role of geosynthetics in mitigating failure risks and enhancing the resilience of embankments constructed with DM.

Keywords-embankment; geosynthetic; bamboo pile; slope stability; dredged material

I. INTRODUCTION

The rapid increase in population in recent years has led to a significant rise in the demand for water supply. Lakes play a critical role in meeting this need, serving as vital sources of water. However, the quality and quantity of lake water are increasingly threatened by the pollution from domestic, industrial, and agricultural waste, rendering it unsuitable for consumption without additional treatment [1]. Furthermore, the excessive withdrawal of water from lakes can result in declining water levels and the degradation of lake ecosystems [2]. Sedimentation poses a significant challenge to lake ecosystems, leading to the accumulation of material at the lakebed. This process reduces the lake's storage capacity and diminishes its ability to retain rainwater, thereby increasing the risk of flooding in the surrounding areas during periods of heavy rainfall [3, 4]. One potential solution to the issue of sedimentation is dredging, which involves the removal of accumulated silt from the lakebed [5]. However, it is essential to manage the outcomes of dredging operations effectively to mitigate their environmental impact, especially when dealing with large volumes of DM. A sustainable approach involves repurposing DM to construct artificial islands near the original lake. This approach eliminates the need for off-site disposal and enables the beneficial use of DM in forming a functional landmass. Nevertheless, it is important to also consider the sedimentary nature of the DM and its quality to manage waste for artificial islands. Nevertheless, the characteristics and quality of DM must be carefully evaluated to ensure effective utilization and environmental sustainability. According to [6], DM typically consists of a mixture of particles, such as sand, silt, clay, and shells. Table I provides an overview of the DM sources, derived from natural formations and sedimentation processes.

TABLE I. DREDGED MATERIAL SOURCES

Source	Description	Reference
Land Areas	Waterbed sediment resulting from soil erosion, bank erosion, and bedload transported through waterways.	[6, 7]
	Sediments originating from mineral erosion, organic material, and soil erosion from upstream areas and riverbanks.	[8, 9]
	Mud, sand, and silt accumulated in channels, bays, and marinas due to upstream sediment erosion.	[9-11]
	Soil erosion from uplands and hillslopes contributing to sedimentation.	[12, 13]
Marine Areas	Particles transported from rocks and soil, submarine volcanism, chemical precipitates from seawater, and extraterrestrial materials deposited on the seafloor.	[14, 15]
	Materials accumulated on the seafloor through volcanism, biological productivity, and hydrothermal vent activity.	[15, 16]
	Deposits from marine organisms, organic matter, minerals precipitated from seawater, and volcanic products.	[17]

A study conducted by the United States Environmental Protection Agency (USEPA) in 1991 revealed that excessive sedimentation can cause significant environmental problems by blanketing the aquatic ecosystems, leading to environmental damage [6]. Consequently, the design of artificial islands must carefully address safety considerations, including construction methods, to prevent potential failures, particularly those resulting from extreme rainfall.

Lake Tempe, located in South Sulawesi, is the second-largest lake in the region, covering an area of approximately 350 km^2. The lake spans 51 villages and 10 subdistricts and is situated at geographic coordinates 4°00'0" - 4°10'00" South Latitude and 119°50'00" - 120°5'00" East Longitude. It receives inflow from 23 rivers, forming part of the Bila and Walanae watersheds [18]. Sedimentation has significantly reduced Lake Tempe's storage capacity, adversely affecting its water level [19]. The catchment area surrounding the lake experiences an estimated erosion rate of 600,000 cubic meters per year, equivalent to a sediment thickness of approximately 0.4 centimeters annually [20]. This sediment accumulation has led to siltation, impairing Lake Tempe's ability to accommodate incoming water during the rainy season. As a result, excessive water spills over, posing a severe flood risk to the nearby villages and endangering the local populations. During the rainy season, Lake Tempe undergoes substantial water level increases, highlighting the importance of flood mitigation measures [21]. To address this issue, the Ministry of Public Works and Housing implemented a comprehensive dredging plan to restore the lake's capacity. Instead of disposing of the DM elsewhere, it was utilized to construct artificial islands around the lake, while flood embankments were subsequently built around these islands to prevent flooding.

Despite these efforts, two recorded incidents of flooding in May 2018 and 2019 led to the collapse of flood embankments on one of the artificial islands. These failures underscore the need to evaluate Lake Tempe's rising water levels and their impact on the stability of flood embankments. The rising water levels remain a critical concern. Figure 1 illustrates the artificial islands constructed using sediment excavated from Lake Tempe.

Fig. 1. Artificial island in Lake Tempe.

A previous study focused on one of the three islands, analyzing the flooding and embankment failures caused by overtopping [22]. However, appropriate embankment designs that align with the properties of the materials derived from the dredging of Lake Tempe sedimentation have yet to be identified. Enhancing embankment stability can be achieved through the use of geosynthetics in soil reinforcement [23, 24]. Additionally, incorporating bamboo piles as soil reinforcement has been shown to improve stability [25].

This study aims to determine the optimal height of the embankment and evaluate soil reinforcement methods utilizing geotextiles and bamboo piles to ensure the slope stability of the embankment.

II. METHODOLOGY

The analysis for this study was formulated based on hydrological data and geotechnical factors. The embankment design focused on two key elements:

- Establishing the embankment height.
- Selecting an appropriate soil foundation reinforcement technique.

The hydrological analysis utilized models with the Q_{20} and Q_{50} return periods, whilst the geotechnical analysis was executed employing the Plaxis software. The data were used to forecast the flood water levels, which influenced the determination of the embankment height. Additionally, the soil reinforcement methods incorporating geotextiles and bamboo piles were evaluated to ensure the slope stability of the embankment.

A. Hydrology Analysis

For the hydrological analysis, reservoir routing was conducted to calculate Lake Tempe's elevation for the Q_{20} and Q_{50} return periods. This analysis provided critical inputs for assessing the embankment height necessary to mitigate flood risks.

B. Geotechnical Analysis

A geotechnical analysis was performed to assess the soil foundation for embankment reinforcement using two approaches: geosynthetics and bamboo piles.

1) Geotextile Reinforcement

Geotextiles were embedded in the soil as reinforcing agents, creating a composite material with enhanced strength and deformation characteristics compared to the unreinforced soil [23]. The three critical mechanical properties of the geotextiles utilized for reinforcement included the tensile modulus, tensile strength, and surface friction.

2) Bamboo Pile Reinforcement

Bamboo was chosen as a reinforcement material for soft soil due to its cost-effectiveness, environmental sustainability, and high tensile strength [26]. The maximum force of embankment foundation soil without bamboo piles, P_{req} is defined as [27]:

$$P_{req} = P_{fill} + P_{found} \quad (1)$$

For soil reinforced with bamboo piles, the maximum force (P^*_{req}) is given by:

$$P^*_{req} = P_{fill} + P^*_{found} \quad (2)$$

$$P^*_{req} = \frac{1}{2} K_a \gamma_b H_b^2 + \mu_r^* s_{u0} L_x \quad (3)$$

where:

γ_b: Hulk density of the fill embankment,

H_b: Height of the fill embankment,

s_{u0}: Undrained shear strength of the soil at ground surface,

L_x: Distance from the embankment toe,

μ_r*: Coefficient of friction between the base of the embankment and bamboo piles on soft soil,

K_a : Active earth pressure coefficient.

III. RESULTS AND DISCUSSION

A. Hydrology Analysis

The initial phase of this study involved a hydrological analysis to determine Lake Tempe's water levels for the Q_{20} and Q_{50} recurrence periods. To achieve this, a hydrological model of the Lake Tempe watershed was developed. The precision of the water level estimates for these recurrence periods relied heavily on the calibration and validation of the model to ensure accurate results. The first stage of the hydrological analysis was the calibration of the model. This calibration utilized data from two flood events, specifically those occurring between May 2002 and June 2019. The outcomes of this modeling process provide calibration results as detailed in [22]. Figures 2 and 3 illustrate the outcomes of model's adjustments using these two flood events. The blue line represents the results generated by the hydrological model, while the black line represents the observed water elevation.

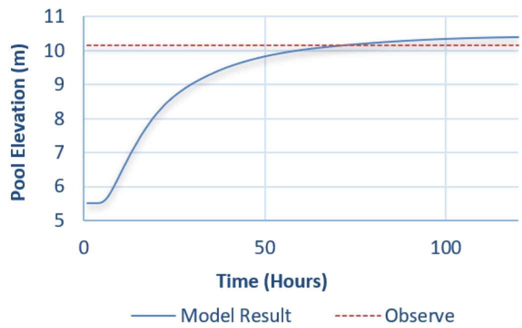

Fig. 2. Flood modeling (May 2022).

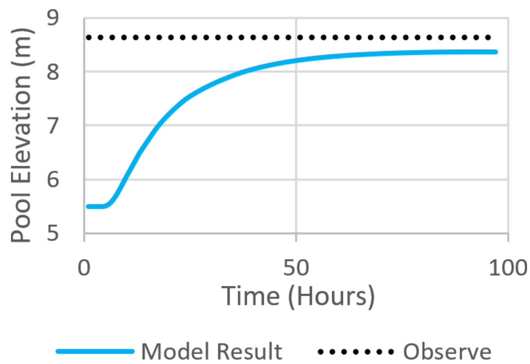

Fig. 3. Flood modeling (June 2019).

Figure 2 demonstrates a strong agreement between the modeled and observed elevations, indicating excellent calibration. Specifically, the modeled peak pool elevation was 10.4 m, closely aligning with the observed peak pool elevation of 10.15 m. This results in a discrepancy of only 2.4%, underscoring the accuracy of the calibration process. Similarly, Figure 3 displays excellent agreement between the modeled and observed data. The modeled peak pool elevation was 8.36

meters, while the observed peak pool elevation was 8.63 meters, resulting in a discrepancy of 3.1%. Overall, the average discrepancy across the modeled and observed pool elevations was calculated at 2.75%, demonstrating that the model was well-calibrated and reliable.

Following the calibration process, a verification step was conducted to validate the adjusted model and ensure its accuracy. For this verification, a significant flood event from May 2018 was utilized. This event is particularly relevant as it represents the most substantial flood following the dredging of sediment and the subsequent use of the sediment to construct the artificial island. Figure 4 portrays the validation process, which yielded favorable results. The modeled peak pool elevation was 9.12 meters, closely aligning with the observed peak pool elevation of 9.2 meters, resulting in a minimal discrepancy of 0.8%. This outcome confirms that the model was effectively calibrated and validated, making it suitable for determining the Q_{20} and Q_{50} return period floods.

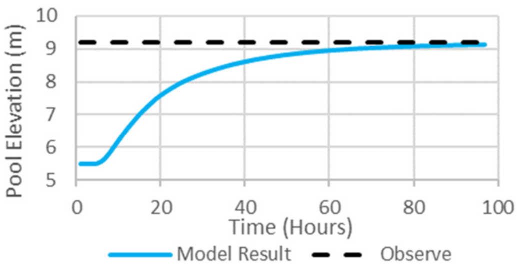

Fig. 4. Verification result on May 2018 flood event.

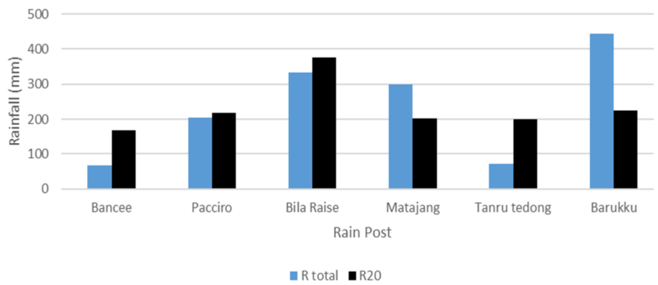

Fig. 5. Actual rainfall and Q_{20} return period rainfall.

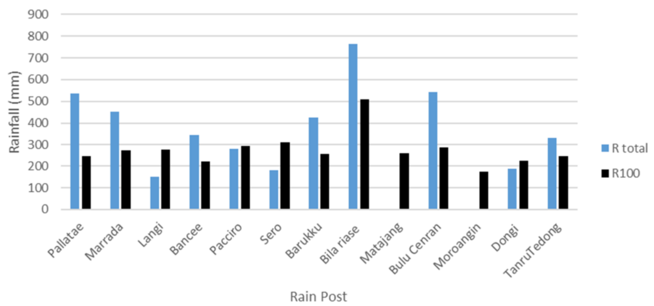

Fig. 6. Actual rainfall and Q_{50} return period rainfall.

To estimate the Q_{20} and Q_{50} return period flows, a frequency analysis of the rainfall data was conducted. The results of this analysis are shown in Figure 5 and 6, presenting a comparison between the actual rainfall and frequency analysis results for flood events. The blue bars represent the actual rainfall, while the black bars represent the rainfall derived from the frequency analysis. Notably, some rainfall stations exhibited nearly identical values for both the Q_{20} and Q_{50} return periods. In cases where actual rainfall data were unavailable during the calibration and validation processes, they were supplemented with rainfall data derived from the frequency analysis. Based on this analysis, the June 2019 flood event corresponds to a Q_{20} return period, while the May 2018 flood event corresponds to a Q_{50} return period. From these findings, it can be concluded that a flood pool elevation of 8.36 meters corresponds to a Q_{20} return period, while a flood pool elevation of 9.12 meters corresponds to a Q_{50} return period.

B. Geotechnical Analysis

A comprehensive geotechnical analysis was conducted as a critical component of this study, focusing on slope stability. This analysis is essential for evaluating the potential impacts of fluctuating Lake Tempe elevations, particularly during extreme events with Q_{20} and Q_{50} return periods, on the stability of the flood embankment surrounding the reclamation island. The slope stability analysis plays a vital role in geotechnical engineering by assessing the integrity of both natural and engineered slopes under various conditions. In the case of flood embankments, these analyses are crucial to ensuring the structural resilience of protective barriers against hydraulic pressures exerted by water bodies, such as Lake Tempe. To enhance the accuracy of the slope stability analysis, additional soil investigations were carried out to characterize the soil composition. The results of these investigations revealed a stratified soil profile, as depicted in Figure 7.

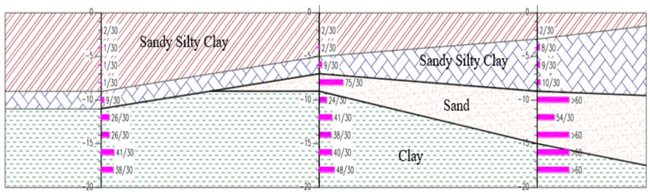

Fig. 7. Soil stratification.

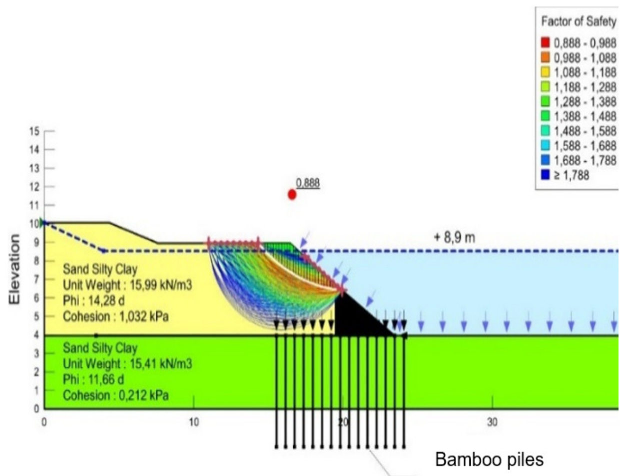

Fig. 8. Slope stability analysis on Q_{20} return period elevation reinforced using bamboo piles.

The uppermost layer of the soil profile comprises soft sandy silty clay, with a thickness ranging from 2 to 9 meters and an SPT N-value of ≤ 2 blows/30 cm. Beneath this layer lies sandy silty clay of a varying stiffness, ranging from stiff to very stiff, with SPT N-values between 8 and 18 blows/30 cm. The next layer is characterized by very dense sandy soil, exhibiting an SPT N-value exceeding 50 blows/30 cm. The deepest layer identified in this study is clay with a very stiff to hard consistency, featuring SPT N-values greater than 26 blows/30 cm. Soil investigations were terminated at a depth of 20 meters. Based on these stratigraphic observations, several correlations for determining the soil's shear strength have been integrated into the analysis model, as displayed in Figures 8-10.

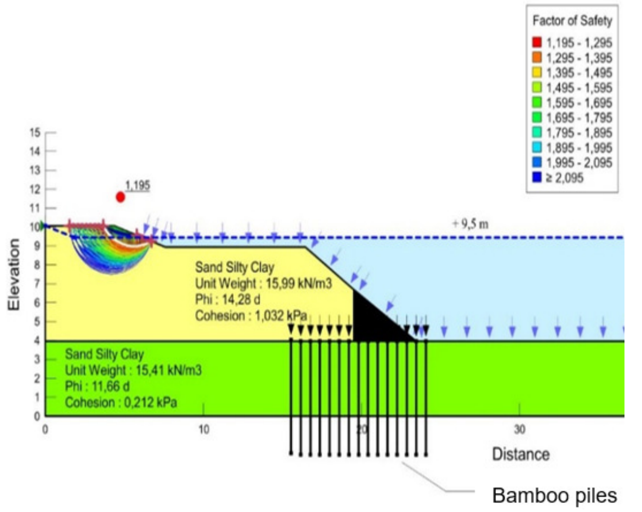

Fig. 9. Slope stability analysis on Q_{50} return period elevation reinforced using bamboo piles.

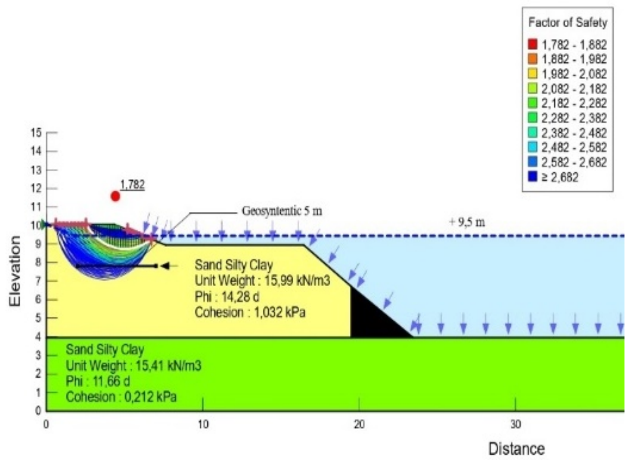

Fig. 10. Slope stability analysis on Q_{50} return period using geosynthetic reinforcement.

The analysis of the flood embankment without soil reinforcement reveals a factor of safety of 0.847 which is significantly below the recommended minimum safety factor of 1.25, as outlined by regulatory standards [28]. This deficiency highlights a critical vulnerability, signaling a heightened risk of slope failure, particularly during extreme flood events associated with a Q_{20} return period or greater. Historical events, such as the May 2018 and June 2019 floods, underscore the severe consequences of insufficient embankment stability, emphasizing the need for urgent corrective measures to prevent future failures. To address these issues, two alternative reinforcement strategies -bamboo piles and geosynthetics- were evaluated for their potential to enhance the embankment's structural integrity. Both solutions offer distinct benefits, including cost-effectiveness, environmental sustainability, and engineering efficiency [29]. These interventions aim to strengthen the embankment, improving its resistance to lateral forces and significantly reducing the risk of slope instability. The preliminary results from the application of bamboo piles as a reinforcement mechanism reveal incremental improvements in slope stability, as reflected in the factor of safety. The analysis indicates factor of safety values of 0.888 for the Q_{20} return period and 1.195 for the Q_{50} return period, demonstrating a notable enhancement compared to the unreinforced condition. Despite these improvements, the factor of safety remains below the critical threshold of 1.25 [28], signaling persistent vulnerabilities in embankment stability. Given the limitations of bamboo piles, the study further investigates the efficacy of geosynthetics as a reinforcement option. Geosynthetics, recognized for their high tensile strength and adaptability, were integrated into the slope stability model using a material with a tensile strength of 20 kN/m. Comprehensive analyses were conducted to evaluate the impact of geosynthetic reinforcement on embankment stability under varying hydrological conditions. The results of the geosynthetic reinforcement analysis, presented in Figure 10, demonstrate significant improvements in the embankment stability parameters. Notably, the factor of safety surpasses the critical threshold of 1.25 during a Q_{50} return period, highlighting a robust enhancement in slope stability. These findings affirm the efficacy of geosynthetics as a viable solution for fortifying embankment resilience and mitigating the risks associated with slope instability.

IV. CONCLUSIONS

This study underscores the pressing challenges posed by increasing water levels in Lake Tempe, particularly their impact on the structural integrity of flood embankments during extreme hydrological events. The analysis highlights that without adequate reinforcement, the embankment's stability is severely compromised, with safety factors plummeting to critical levels (e.g., 0.807 for a 20-year (Q_{20}) return period flood). These findings reflect the urgent need for effective slope stabilization measures to mitigate the failure risks and safeguard the surrounding communities. To address these vulnerabilities, two alternative slope reinforcement strategies were evaluated: bamboo piles and geosynthetics. The analysis reveals that while bamboo piles provide marginal improvements in stability, they fail to meet the minimum acceptable safety threshold, rendering them inadequate for mitigating the embankment failure risks. Conversely, the incorporation of geosynthetics as reinforcement demonstrates significant potential in enhancing slope stability. Following geosynthetic reinforcement, the safety factors improve markedly, achieving values well above the critical threshold for stability. Additionally, the required embankment heights to accommodate the Q_{20} and fifty-year (Q_{50}) flood events were determined to be 8.36 meters and 9.2 meters, respectively.

The findings of this study highlight the superiority of geosynthetics over bamboo piles in ensuring embankment stability under extreme hydrological conditions. The geotechnical analysis confirms that geosynthetic-reinforced embankments offer robust and reliable solutions to mitigate the slope instability risks, thereby safeguarding the integrity of the flood embankment and surrounding areas.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of Bina Nusantara University under the scheme of Penelitian International Binus (PIB) with contract number: 069C/VRRTT/II/2024 and contract date: March 18, 2024.

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