

Integrating Forensic Analysis and Sustainable Design for Slope Stabilization: A Case Study Using Waste Tire-Filled Gabion Structure (WTFGS)

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Abstract

This study presents a forensic investigation and geotechnical modelling of a landslide disaster and associated slope failure that adversely affected nearby infrastructure. The investigation involved geological mapping and geotechnical investigation through borehole drilling, followed by laboratory testing to characterise the physical index and engineering properties of the soil. Slope stability analyses were performed using SLOPE/W to show the stability analysis (Factor of Safety - FOS) for both the current failed slope condition and a proposed remediation design that incorporates sustainable materials. The proposed solution utilised a waste tire-filled gabion structure (WTFGS) as a sustainable slope retaining technique. Results indicated that the FOS for the existing slope was 0.979, classifying it as unstable. However, with the implementation design of WTFGS, the FOS improved to 1.580, indicating a stable slope in accordance with standard guidelines. These findings demonstrate that using waste materials to replace conventional materials is a practical remediation technique and a sustainable solution for slope stabilisation in new construction and slope repair applications. The integrated methodology strengthens failure assessment and supports the development of effective, sustainable slope stabilization solutions.

1. Introduction

On the early morning of 5th January 2021, two (2) landslide events were reported in Gambang Damai Residential, Kuantan, Pahang, Malaysia. The landslides significantly impacted a total of six (6) semi-detached residential units, resulting in the complete collapse and destruction of two (2) houses, while the remaining four (4) sustained structural damage [1]. In addition to the residential damage, the landslide-induced ground movement compromised nearby infrastructure, including roads and drainage systems. Figs. 1(a) and 1(b) illustrate the extent of the landslide-affected area, showing the destruction to housing units, roadways, and drainage facilities caused by the incident. The incident resulted in the evacuation of 66 households, and the area was declared a red zone (landslide-prone area). Two (2) residential structures situated on a hillside experienced collapse as a result of slope instability triggered by intense and prolonged rainfall, according to preliminary assessments by an expert. The failure caused substantial damage to the surrounding environment and raised apprehension about the

stability of neighbouring structures within the affected area. Given the occurrence of a landslide disaster in the area, which resulted in the destruction of residential structures and infrastructure, it is crucial to compile and consolidate a comprehensive reference data. Such data will support the development of effective preventive measures, strengthen disaster management systems, and inform future recovery and maintenance strategies.

As of January 2026, approximately three (3) researchers have been identified for conducting studies on landslide and slope failure in the area. According to a study conducted by Zolkepli *et al.* [2], the use of unmanned aerial vehicles (UAVs) for slope mapping at the Gambang Damai Residential area was explored, focusing on parameters such as the perimeter, area, and volume of selected regions. They stated that traditional slope mapping techniques are often time-consuming and challenging, particularly in hilly areas [2], [3]. Their research employs advanced UAV technology to capture high-quality images, which are used to generate mapping outputs such as digital elevation models (DEM) and digital orthophotos. Meanwhile, a study performed by Zaini *et al.* [4] suggested that to improve the stability of the slope, the presence of trees in the slope structure can impact the soil matric suction, where water uptake by tree roots influences soil moisture levels. They conducted field monitoring to compare matric suction in the presence and absence of an *Alstonia Angustiloba* tree at the top of the slope, using tensiometers, gypsum blocks, and a rain gauge. The results showed that the presence of the tree significantly increased matric suction near the tree trunk, particularly at shallow depths. Variations in suction due to tree water uptake and rainfall suggest that preserving mature trees can enhance soil shear strength, particularly in slope factor safety. Another study conducted by Zolkepli *et al.* [5] focused on the properties of tropical residual soil, with several experiments assessing its index and engineering properties. The typical soil identified in the study area is a sandy silt with high plasticity, and slope stability analyses have already been performed using SLOPE/W software. The findings show the factor of safety (FOS) of the selected slope in the study area.



Fig. 1 Landslide area (a) Aerial photogrammetry of the failure area; (b) Collapsed house affected

Alamanis & Ionannis [6] stated that slope failure, particularly in landslides, remains a critical issue in geotechnical engineering, with significant implications for infrastructure, human safety, and environmental sustainability. The slope failure event in Malaysia was mainly triggered by antecedent rainfall and human activities [7] – [9]. Noor *et al.* [7] claimed that antecedent rainfall increases pore-water pressure in saturated soil, reducing shear strength and weakening the bonding between soil particles, which leads to slope failure. In Malaysia, a study conducted by Akter *et al.* [10] indicates that the country has documented a yearly increase in landslide disasters. The landslide forensic statistics from the Slope Engineering Branch (SEB) in Malaysia show that human factors were responsible for around 57% of slope failures, index factors contributed to 29%, and various geological factors accounted for 14% [11]. In a rough look, the landslide occurs when the forces acting on a slope exceed its resistance, often triggered by factors such as heavy rainfall, earthquakes, human activities (e.g., deforestation and construction), and unfavourable geological conditions [12] – [14]. The mechanisms behind slope failure include rotational and translational slides, debris flows, and topples, each with distinct characteristics and triggers [15].

Understanding these failure types has led researchers and engineers to develop and apply various analytical techniques for assessing slope stability, such as limit equilibrium methods (LEM) [16] – [20], finite element modelling (FEM) [16], [21] – [24], and forensic investigations (FI) [25] – [27], which analyses post-failure conditions to identify failure mechanisms. Numerical analysis, particularly advanced finite element modelling,

offers detailed simulations of slope behaviour, improving the understanding of instability. Remediation measures include engineering solutions such as slope regrading, drainage systems, and retaining walls, as well as natural approaches like vegetation and bioengineering, to reinforce slopes sustainably. These related issues have garnered attention from researchers like Kazmi *et al.* [28a]; Kazmi *et al.* [29b]; Zabidi *et al.* [30]; Goh *et al.* [25]; Gue *et al.* [31] and Liew *et al.* [32] who have studied slope failures in Malaysia and offered general recommendations along with possible mitigation strategies.

With the rapid advancement of modern technology in the automotive industry, the volume of waste tire generation has increased significantly, driven by the growing number of vehicles produced nationwide [33] – [35]. Dabic-Miletic *et al.* [36] insisted that improper disposal of end-of-life tires has emerged as a pressing environmental concern, contributing to a variety of ecological and public health issues. Addressing the challenges associated with waste tire management requires a comprehensive and strategic approach to mitigate its adverse environmental impacts and promote sustainable waste handling practices [37]. One promising use of waste tires is in geotechnical engineering, particularly for slope stabilization, whether on an untreated or treated slope [37] – [39]. Traditional methods for slope protection, such as concrete walls and steel reinforcements, are costly and environmentally intensive [40]. In contrast, waste tires provide a durable, elastic, and cost-effective solution, making them an alternative for solving problems more sustainably in slope remediation [41] – [43]. A sustainable slope remediation technique aims to stabilize slopes while minimizing environmental impact and promoting long-term ecological balance. Several methods that are widely adopted are the use of methods like vegetation [44], [45], bioengineered slope protection (BESP) [46], [47], capillary barrier systems (CBS) [45] – [49], geobarrier slope systems (GSS) [49], [50], and recycled waste tire (RWT) materials [41] – [43], [51].

The use of waste tire-derived materials, including tire bales [42], [43], [52], shredded tire chips [42], and tire-soil mixtures [51], has proven to be a technically viable and environmentally sustainable solution for slope stabilization. These materials offer key geotechnical advantages, including reduced unit weight, high permeability, and improved soil shear strength, all of which contribute to enhanced slope stability by reducing the subsoil's normal stress [42]. An experimental study conducted by Hajiazizi *et al.* [52] demonstrated that incorporating waste tires, either as a replacement for or in combination with conventional materials in slope protection structures, can effectively address critical issues related to structural stability and bearing capacity. This method improves the overall ductility and resilience of the structure, thereby enhancing its resistance to failure. The positive impact of using woven waste tires for slope protection stems from their tensile strength and structural reinforcement properties, which effectively enhance gabion wall stability and prevent slope failure [43]. Experimental results done by Apriyono *et al.* [43] show that this reinforcement improves the gabion wall's load-bearing capacity and slope stability by creating a hardening failure model under load.

This study aims to evaluate the effectiveness of the waste tire-filled gabion structure (WTFGS) as a sustainable technique for slope stabilization in landslide-prone areas. Through the integration of desk studies, geological assessments, site investigations, laboratory testing, and geotechnical modelling, the research provides a comprehensive evaluation of the engineering performance and stability improvements associated with the application of waste tires. The findings contribute to the growing body of knowledge on the reuse of waste materials in geotechnical engineering, supporting both environmental sustainability and the enhancement of slope safety.

2. Methodology

The study was conducted in several stages. The first stage involved a desk study focused on gathering preliminary information about the study area. The second stage comprised field measurements in problematic zones, while the final stage focused on data analysis. The desk study aimed to consolidate existing information on the geological setting and topography at both global and local scales, using available reports and maps, as outlined in the subtopics of the methodology section. This research adopted a comprehensive methodological approach to evaluate the effectiveness of the Waste Tire-Filled Gabion Structure (WTFGS) in enhancing slope stability in a landslide-prone area at Gambang Damai Residential.

The methodology began with a forensic investigation of previous landslide events at the selected site to identify the leading causes and patterns of slope failure. The study collected and analysed geological information and historical data on past landslides to support this investigation. In parallel, this research conducted geotechnical investigations, including borehole drilling, to collect geological and geotechnical data and assess subsurface conditions that contribute to slope instability. During the data collection phase, this study conducted detailed subsurface investigations using borehole drilling and extracted soil samples for laboratory testing. These tests aimed to determine the soil's physical index and engineering properties with accuracy.

Subsequently, the study performed slope stability analyses using SLOPE/W software. The initial analysis assessed the current (existing) condition of the slope by calculating its Factor of Safety (FOS). A comparative analysis followed, involving a modelled remediation scenario that incorporated WTFGS as a slope protection

measure. This comparison aimed to evaluate improvements in slope stability and FOS, thereby assessing the viability of waste tire applications as a sustainable slope stabilization solution.

2.1 Study Area

The survey area is at Gambang Damai Residential, Kuantan, Pahang, Malaysia, at an approximate latitude of $3^{\circ} 42' 7.8588$ and longitude of $103^{\circ} 2' 31.4484$ and in UTM coordinates of 282540.667 (Easting) 409448.157 (Northing), as depicted in Fig. 2. This residential area was a relatively new development, with most houses built in the early 2000s. The area is home to a mix of single-storey and double-storey terrace houses, as well as a few semi-detached houses. Gambang Damai Residential is a quiet and peaceful region, with plenty of green space. These areas are commonly found in regions with natural geological uplift or erosion processes and often present challenges for construction and infrastructure development due to variable slope angles, potential instability, and drainage complexities. In geotechnical engineering, hilly areas require detailed analysis and slope stability assessments because they are more susceptible to landslides, soil erosion, and surface runoff issues, particularly during periods of intense rainfall. Proper land use planning, effective slope reinforcement techniques, and environmental management are essential to ensure safety and sustainability in such terrains.

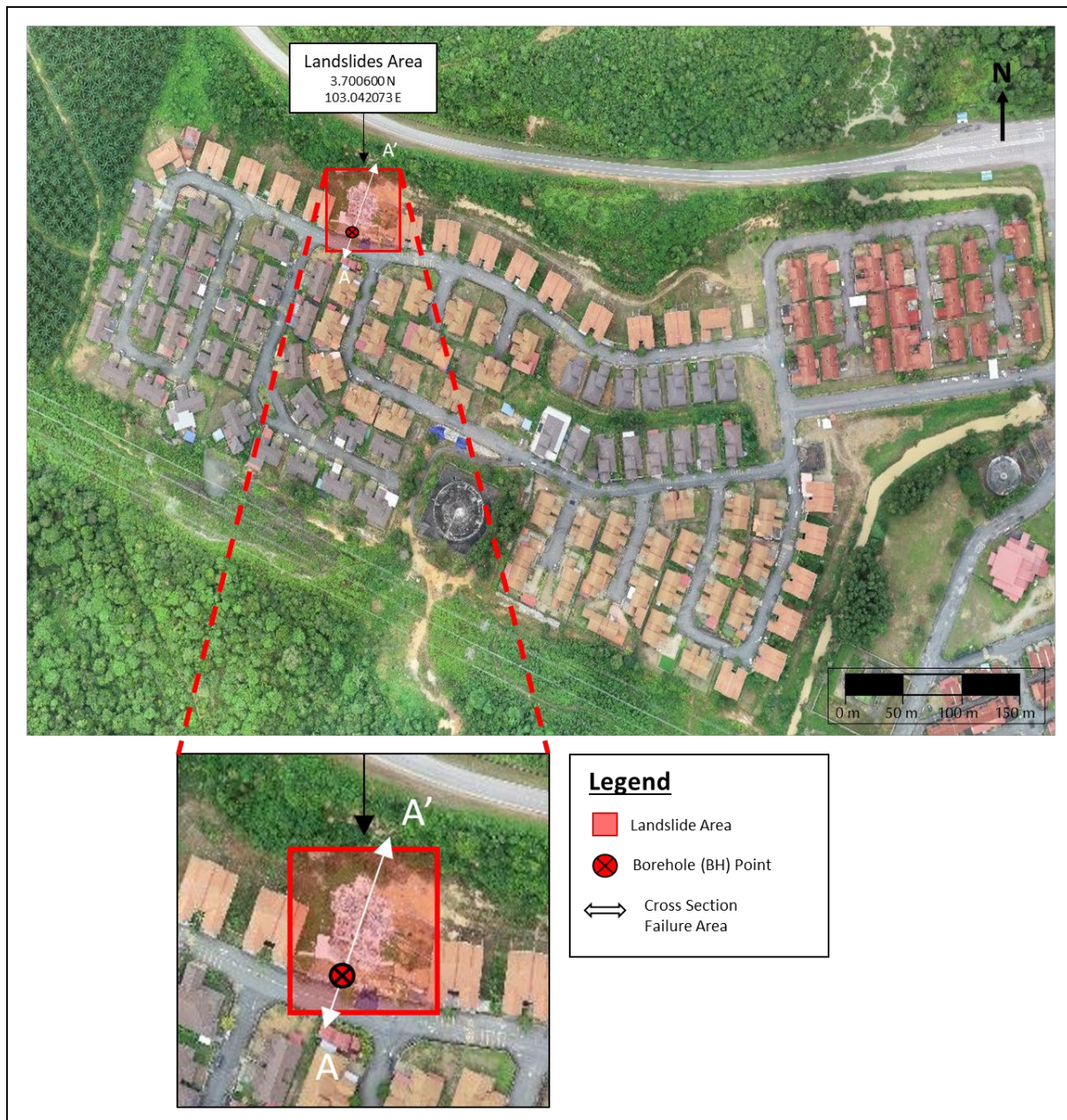


Fig. 2 Location of study and landslide area

2.2 Geological Setting of the Region

In general, the geology of this area mainly consists of Carboniferous metasedimentary rocks, as indicated in the 9th Edition of the Geological Map of Peninsular Malaysia, as shown in modified Figs. 3. Based on Fig. 3, the quaternary deposit forms the study area. It was considered to be part of the Pleistocene epoch. It covers the geological time scale's last two (2) million years. Quaternary of Peninsular Malaysia Deposits are built by the unconsolidated to semi-consolidated sand, gravel, silt, clay and valleys. This formation occupies about 20% of the land in Peninsular Malaysia [53]. In the landslide area, geology was dominated by weathered alluvial soil underlying the metasedimentary rocks. Most of the metasedimentary rocks in this area result from contact metamorphism due to the granitic intrusion in the deeper zone. Geological field studies by previous researchers were conducted by Fitch [54] in the area around Kuantan, Pahang, Malaysia, mapping the Syit 82 (Sungai Lembing, Kuantan, Pahang, Malaysia) area from 1981 to 1986. Based on their study, these metasedimentary rocks generally consist of rocks mainly composed of slate, shale, sandstone, and phyllite, with a few limestone lenses found in some areas. However, no limestone lenses were identified within the boundaries of the residential area.

Detailed geological mapping of this residential area and its surroundings revealed that it is covered with perfectly weathered soil from metasedimentary rocks. The residual soil resulting from the weathering process of metasedimentary rocks is clayey-sandy. Rock outcrops were only found in a few localities, mainly slate, phyllite, and shale interbedded with sandstone. This rock outcrop is slightly to completely weathered in several locations around the park, and the road cut slope is near this residential area. This rock slopes towards the northeast with a slope angle between 60° and 70° degrees. There are at least two sets of sharp cuts cutting this rock. The shale rock is soft and has a weak plane. Additionally, the residual soil of the granite rock is sandy-clayey, and the granite rock has undergone complete weathering.

Meanwhile, alluvial deposits identified in the river valley area consist of geological materials such as clay, sand and gravel. In the area around this residential area, metasedimentary rocks are also exposed, mainly consisting of metamudstone, metasilstone and a little metasandstone. The main strike of the exposed rock layers here is N1160° with a dip of 880° SSW, while the main rock sets are N32°, N100° and N1220° with dips of 640° WNW, 380° WNW and 200° NNE, respectively. In addition, younger shale, mudstone, and sandstone layers were found in the eastern part of the survey area (outside the study area boundary). The sandstone has a very fine grain size, whitish to yellowish in colour, and a round and angular grain shape. Sandstone comprises quartz, feldspar and lithic fragments, while mudstone and shale comprise clay, feldspar, and other carbonate minerals. As for the shale and mudstone, both are brownish to black and have very fine-grained and well-sorted features with little to no fossil or trace fossil presence. These indicate that this area was a deep marine environment. Tectonic movement or sea level changes have resulted in the current elevation and condition of the study area.

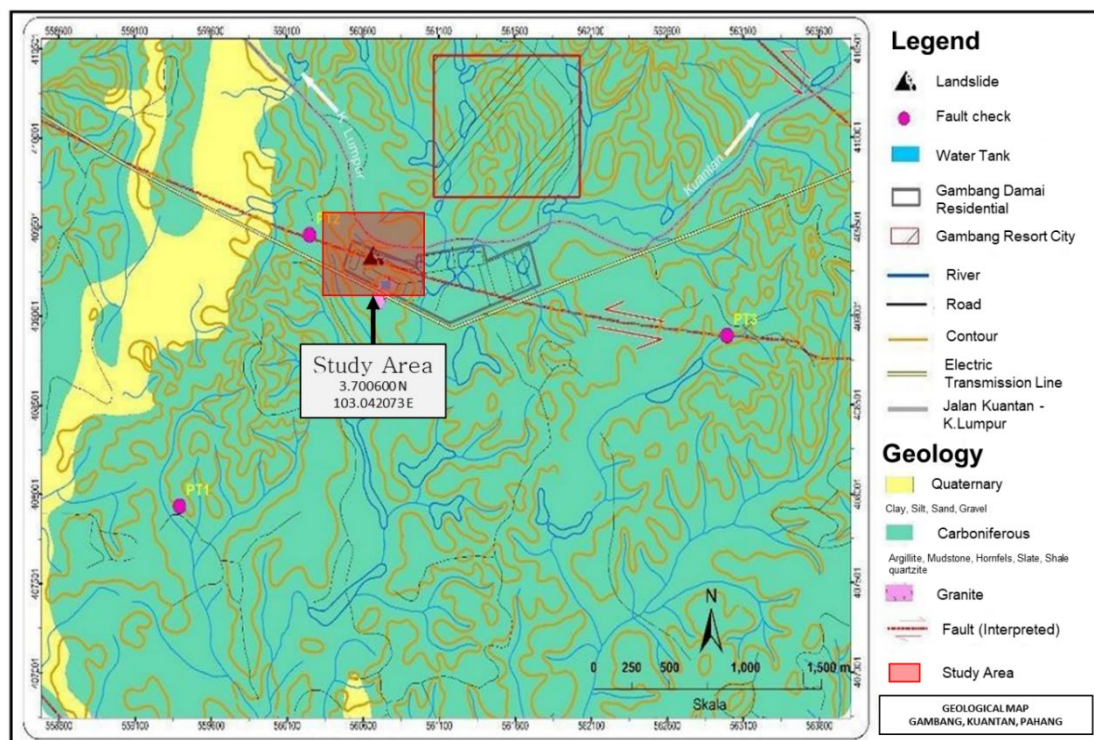


Fig. 3 Geological map of the investigation area and its surroundings, modified from Department of Mineral & Geosciences, Malaysia [55], [56]

2.3 Geometry of the Landslide Area

Fig. 4 illustrates a cross-sectional profile of a slope with distinct zones, including a road area, a failure (landslide) area, and an earth drain. The failure zone spans approximately 30 meters, indicating significant instability, likely influenced by factors such as soil erosion, water infiltration, and external loading from nearby infrastructure. The earth drain at the slope's base may contribute to further instability through toe erosion and groundwater infiltration, weakening the soil structure. With a total length of more than 80 meters and varying elevation levels, the slope poses potential risks to infrastructure and public safety. According to Daud *et al.* [57], engineering solutions such as retaining structures, soil reinforcement, proper drainage systems, and vegetation cover should be considered to mitigate further failure. The cross-sectional alignment A-A' delineates the failed slope segment within the study area, providing a detailed representation of the affected zone's collapse geometry and subsurface profile. The geometry shown has been used as a reference in the design of slope stabilization, and slope analysis was carried out using SLOPE/W software. In addition to soil parameters, the cross-section measurement of the slope is important for conducting slope stability analysis.

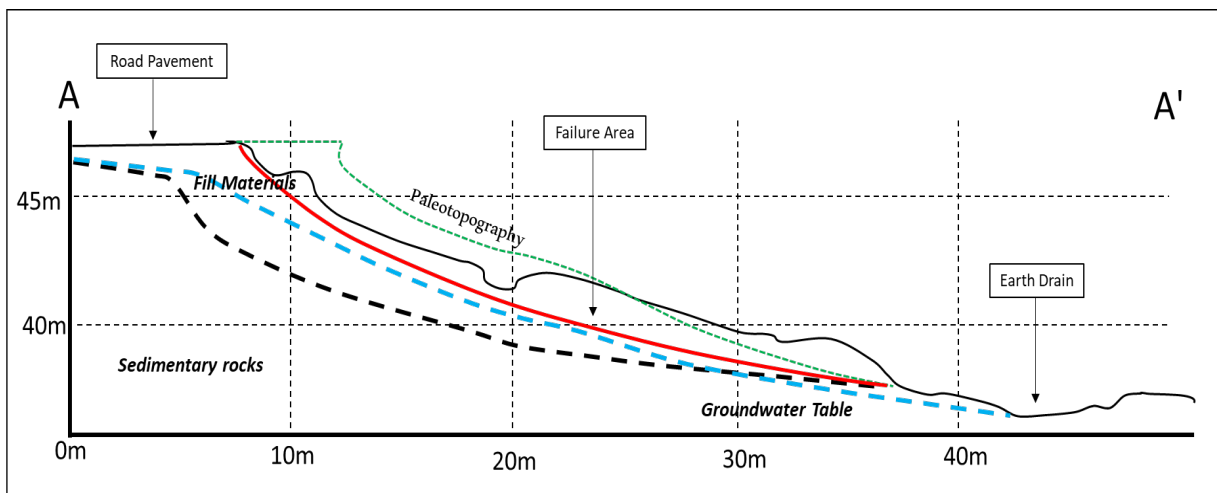


Fig. 4 Cross section A - A' shows the geometry of the landslide area

2.4 Geotechnical Sites Investigation

The geotechnical investigation for this study involved detailed site investigation (SI) work, primarily consisting of rotary borehole drilling and in-situ testing to characterize subsurface conditions [58]. A single borehole was strategically located at the top of the slope to obtain representative subsurface data, including lithology, groundwater conditions, and soil engineering properties. Borehole drilling was carried out to a depth of 45 meters, with continuous logging of the soil profile. Soil samples, both disturbed and undisturbed, were retrieved at selected intervals and subsequently subjected to laboratory testing. The tests conducted included determining index properties (moisture content, Atterberg limits, and particle size distribution) and strength parameters, such as triaxial shear tests, following procedures in accordance with British Standard (BS) 1377:1975. In-situ Standard Penetration Tests (SPT) were also performed at regular depth intervals using a split-barrel sampler and a standard self-tripping hammer setup to estimate relative density and consistency.

Due to site constraints, only a single borehole was completed for this investigation. As such, it was assumed that the derived soil profile, engineering parameters, and water table level reasonably represent the entire slope cross-section. While this introduces some limitations to subsurface variability analysis, the borehole location and stratigraphy were deemed representative based on preliminary geomorphological assessment and visual slope uniformity. Also, author as Yusof *et al.* [58] stated that due to the absence of several site-specific parameters, reasonable assumptions were made, and the corresponding values were derived from relevant literature, geological interpretation, and engineering judgment [59]. This approach is common in preliminary slope stability studies and serves as a practical basis for numerical modelling and design input parameters in this case.

2.5 Laboratory Experiments on Soil Physical Index and Engineering Properties

Laboratory testing was conducted to obtain detailed information on the physical index properties and engineering characteristics of the soil at specific slope locations within the study area. This information was then utilized to determine the characteristics and behavior of the soil for various geotechnical applications, including slope stability analysis. Laboratory tests provided a more comprehensive understanding of the soil properties encountered in the area by performing multiple tests in accordance with British Standard 1377-2:1990 for Soil

Classification. In addition to assessing the physical index properties, the engineering properties of the soil were also evaluated through laboratory experiments for determining soil shear strength. The tests were categorized based on the type of soil samples collected: (1) disturbed soil samples for determining physical index properties, and (2) undisturbed soil samples for evaluating engineering properties. The primary physical index tests performed included particle size distribution (PSD), Atterberg limits (AL), specific gravity (SG), and natural moisture content (MC). The engineering characteristics of the soil were assessed using the consolidated isotropic undrained (CIU) triaxial test method. Experimental procedures were conducted in accordance with British Standard BS 1377: Part 1–9: 1990. Table 1 summarizes the tests carried out to determine the index and engineering properties of the soil samples collected from the study area.

Table 1 Tests carried out to characterise the physical index and engineering properties of soil sample

Physical Index and Engineering Properties	Test	Standard and Code
Natural moisture content (MC)	Moisture content	BS 1377: Part 2: 1990, 3
Particle size distribution (PSD)	Sieve analysis & Hydrometer	BS1377: Part 2: 1990, 9.3
Liquid limit (LL), Plastic limit (PL), and Plasticity index (PI)	Atterberg limit	BS 1377: Part 2: 1990, 4 & 5
Specific gravity (SG)	Small pyknometer	BS1377: Part 2: 1990, 8.3
Shear strength	Triaxial shear test	BS1377: Part 1-9: 1990 / BS1377: Part 8: 1990:7

2.6 Conceptual Framework and Structural Configuration of Waste Tire-Filled Gabion Structure (WTFGS)

The conceptual framework for the waste tire-filled gabion structure (WTFGS) has already been developed to explore the feasibility of using recycled waste materials for slope stabilization while addressing environmental concerns related to tire disposal. WTFGS proposed in this study integrates the conventional gabion wall method with sustainable materials by utilizing tire bales as the primary infill. Traditionally, gabion walls are constructed using galvalume-coated wire mesh baskets filled with stones, offering structural integrity and permeability for slope stabilization. In this design, the gabion baskets were fabricated with dimensions of 2.0 meters in length and 1.5 meters in width and height. The total installation on-site was estimated to cover an area with a height and width of approximately 7.5 meters, and a total length of 20 meters, sufficient to stabilize the targeted landslide-prone zone. The tire bales used in this structure were formed and sized to closely match the internal dimensions of the gabion baskets, ensuring compatibility and efficient filling. As depicted in Fig. 5, the design considered key factors such as load distribution, permeability, and interlocking behavior of tire fill. The placement geometry and layer thickness were determined based on the slope's geotechnical profile and expected loading conditions. This framework served as the basis for further numerical modelling and field performance evaluations, allowing assessment of the WTFGS's effectiveness in enhancing slope stability and sustainability.

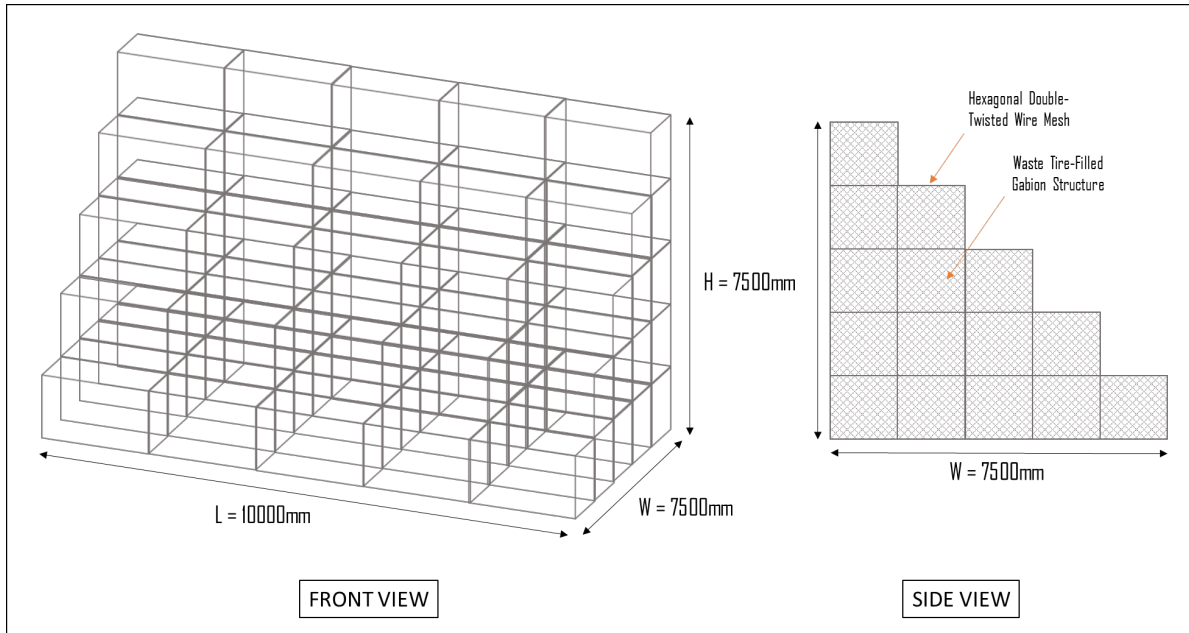


Fig. 5 Structural configuration of waste tire-filled gabion structure (WTFGS) with front and side view design

2.7 Geotechnical Analysis of Slope Stability and Design Standards

SLOPE/W is commercial computer software that primarily verifies slope stability results in the location study; a commercial software package will provide immediate proof of slope stability results in the location study. As stated by Kassim & Kasim [60], Goh et al. [25] and Siregar et al. [21], a piece of commercial software known as SLOPE/W was utilized to carry out fundamental tests on the outcomes of slope stability. This study was conducted using the software to compute slope FOS with limit equilibrium methods (LEM), evaluating the stability condition of the slope, including both the existing and remedial conditions (WTFGS). The LEM has long been a fundamental approach in geotechnical engineering and remains widely adopted in contemporary practice [17]. The advancement of modern graphical software tools has significantly enhanced the ability to visualize and interpret the underlying numerical mechanisms of this method. However, to compute and analyze the stability of the slope, this software requires several elements or parameters. The most essential aspects are slope geometry and soil parameters, such as physical index (type of soil) and engineering properties (cohesion c' and friction angle ϕ) [61]. From there, components of slope geometry are utilized for the analysis. The information obtained from the laboratory experiments on soil parameters was incorporated into this software to address the soil properties component.

The Guidelines for Slope Design 2010, published by the Malaysian Public Works Department [62], provided a comprehensive framework for slope design and stability analysis. These guidelines incorporate the latest technical requirements, design materials, and engineering practices adopted by PWD Malaysia, ensuring they reflect contemporary advancements in slope engineering. The primary objective of these guidelines is to assist in addressing critical issues related to slope stability, safety, and mitigation measures. Therefore, for this analysis, these guidelines were adhered to, ensuring that the slope stability models and assessments followed the standard requirements and recommendations outlined. The following outlines the geotechnical design criteria for geotechnical works, including the minimum required FOS, as provided in Table 2.

Table 2 The minimum of FOS for untreated and treated slope guidelines from Malaysian Public Works Department [62]

Design of Slope	Mode of Failure	Type of Slope	Value of FOS
Untreated slope	Local & global stability	Cut & fill	1.30
Treated slope	Local & global stability	Cut & fill	1.50

3. Result and Discussion

3.1 Physical Index and Engineering Properties of Soil

A single borehole was drilled at the study site, specifically at the toe of the slope, to obtain representative soil samples for laboratory testing and geotechnical evaluation. The drilling works were carried out over a period of two (2) days using the rotary wash boring method, with the borehole reaching an approximate depth of 25.5 meters. Soil samples were collected at regular intervals to capture variations in subsurface stratigraphy, and both disturbed and undisturbed samples were preserved for subsequent laboratory analysis. Observations made during and after the drilling process indicated that the groundwater level was encountered at a depth of 6.1 meters, three (3) days after the completion of the drilling work. Laboratory tests were performed to determine the physical index properties of the soil, including moisture content, specific gravity, particle size distribution, and Atterberg limits, as well as the engineering properties, such as shear strength parameters (cohesion c' and friction angle ϕ), obtained through the consolidated isotropic undrained (CIU) triaxial test. The soil types were classified based on BS 1377-2:1990 and visual-log descriptions. These properties provided critical insights into the soil behavior at depth and formed the basis for the slope stability analysis and design considerations at the site. Table 3 summarizes the soil parameters at the Gambang Damai Residential area that were used in the slope stability analysis for this study.

As presented in the Table 3, the results of laboratory tests conducted on soil samples obtained from borehole 1 (BH1) at varying depths between 3.75 m and 10.50 m. The laboratory testing was conducted to focus on identifying key physical and index properties essential for geotechnical characterization. In terms of moisture content (MC) testing, the moisture content ranged from 18% to 29%, indicating moderate variability in in-situ water retention across the soil profile. Furthermore, specific gravity (SG) values remained relatively consistent between 2.67 and 2.70, typical for fine-grained soils. The Atterberg limits revealed variations in plasticity, with liquid limits (LL) ranging from 26% to 52%, plastic limits (PL) from 20% to 25%, and plasticity index (PI) between 5% and 27%, suggesting a mixture of low- to medium-plasticity soils. The particle size distribution (PSD) data further supported this classification: sand content was dominant at deeper levels (up to 65% at 10.5 m), while higher clay and silt fractions were observed at shallower depths. Notably, the sample at 5.00 m depth exhibited the highest PL value which is (27%), indicating a more cohesive soil layer that could significantly influence slope stability behavior. These findings provided essential input for defining the subsurface stratigraphy and selecting appropriate parameters for the evaluation conducted.

Table 3 Summary of laboratory data for borehole drilling






Borehole (BH)	Sample Number	Depth (m)	Physical Index Test								
			MC (%)	SG	Atterberg Limit			Particle Size Distribution (PSD)			
					LL (%)	PL (%)	PI (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
BH1	UD1	3.75	19	2.67	34	22	21	2	40	26	32
BH1	M1	5.00	29	2.68	52	25	27	8	37	21	34
BH1	UD2	6.75	23	2.67	41	20	21	0	51	21	28
BH1	M3	8.00	18	2.68	26	21	5	8	63	23	6
BH1	D8	10.50	18	2.70	29	24	5	2	65	26	7

To conduct a comprehensive slope stability analysis, soil parameters were derived primarily from laboratory testing, including engineering properties tests. Engineering properties were determined using the consolidated isotropic undrained (CIU) triaxial test, which provided key geotechnical parameters such as unit weight γ , cohesion c' , and friction angle ϕ . In addition to laboratory results, selected soil parameters were also obtained from previous studies and well-founded assumptions, based on the correlation with soils exhibiting similar geotechnical characteristics. Table 4, the complete set of engineering soil parameters employed in the slope stability analysis, comprises both experimentally measured values and inferred data.

As illustrated in Table 4, it provides a summary of the engineering properties for different soil layers, focusing on the unit weight (γ), cohesion (c'), and friction angle (ϕ) of various soil types. Fill materials and compacted fill have similar properties, are characterized by a unit weight of 18 kN/m^3 , cohesion of 3 kPa, and a friction angle of 28° . These layers (Layer 1 and Layer 2) of soil parameters were also obtained from previous studies and well-founded assumptions, based on the correlation with soils exhibiting similar geotechnical characteristics. In Layer 3, the soil is medium dense silty sand ($10 < N_{SPT} < 30$) with a unit weight of 18 kN/m^3 , similar to the previous layers, but it exhibits an increase in cohesion to 6 kPa and a friction angle of 29° . This reflects a denser and stronger soil,

offering better shear strength and stability than the fill materials. Layer 4 is composed of dense silty sand ($30 < N_{SPT} < 50$), which also has a unit weight of 18 kN/m^3 , but the cohesion remains at 6 kPa while the friction angle increases to 32° . The higher friction angle indicates better shear resistance and higher bearing capacity. Finally, Layer 5 consists of very dense silty sand ($N_{SPT} > 50$), which has a slightly higher unit weight of 19 kN/m^3 , reflecting increased compaction and density. The cohesion remains at 6 kPa , but the friction angle increases to 34° , showing the highest shear strength among the layers. Each successive layer shown increases density, cohesion, and friction angle.

Table 4 Engineering properties of soil

Number of Layer	Types of Soil	Color Label	Unit Weight γ (kN/m^3)	Cohesion, c' (kPa)	Friction Angle, ϕ' ($^\circ$)
1	Fill Materials		18	3	23
2	Compacted Fill		18	3	28
3	Medium Dense Silty Sand ($10 < N_{SPT} < 30$)		18	6	29
4	Dense Silty Sand ($30 < N_{SPT} < 50$)		18	6	32
5	Very Dense Silty Sand ($N_{SPT} > 50$)		19	6	34

3.2 Analysis of Slope Stability by SLOPE/W

Table 5 outlines the geotechnical design inputs used in the slope stability analysis conducted with SLOPE/W software. The analysis adopted the Morgenstern-Price method, a widely accepted LEM that satisfies both force and moment equilibrium conditions [63] – [67]. The slip surface search employed the “Entry-Exit” technique, with movement assumed from “Left to Right”, reflecting the natural failure direction observed at the study area. A structural surcharge load of 10 kN/m^3 was applied to simulate external loads influencing the slope, while the groundwater level conditions were represented using a piezometric level located at 6.2 meters depth. To maintain numerical consistency and solution reliability, the FOS distribution was set to a constant with a tolerance of 0.01 . The model discretization consisted of 30 slices, which provided adequate resolution for capturing slope behavior, and the minimum slip surface depth was defined at 0.1 meters to detect shallow failure surfaces. These parameters were essential for producing a realistic and site-specific slope stability simulation under existing and remedial conditions. For the remedial slope condition, the geotechnical design inputs remained similar in methodology to ensure comparability with the existing condition analysis, with none of the modifications reflecting the incorporation of the WTFGS.

Table 5 Geotechnical design inputs for slope stability analysis

Slope Design Inputs	Unit	Remarks
Geotechnical analysis method	-	Morgenstern-Price
Slip surface techniques	-	Entry-Exit
Slip surfaces direction movement	-	Left to Right
Structural surcharged load	kN/m^3	10
Piezometric level	m	6.2
Factor of safety distribution calculation	-	Constant
Factor of safety tolerance	-	0.1
Number of slices	-	30
Minimum slip surface depth	-	0.1

Figs. 6 and 7 below present the results obtained from the SLOPE/W software analysis using the LEM for the Morgenstern-Price analysis method to compute the FOS of the slope. These computed slope stability analyses

were conducted to assess the FOS in two conditions of slope (existing condition and remedial condition). Before that, the slope stability analysis for the case study is divided into two (2) parts: the analysis of the slope in its existing condition (untreated slope) before applying the remedial measure, and the analysis after applying the WTFGS (treated slope). The WTFGS method proposed in this study involves slope protection using waste tire materials. As stated, and listed in the slope guidelines published by PWD Malaysia, the FOS for untreated and treated slopes must meet the minimum requirement to classify a slope as stable or unstable. The analysis of the existing condition shows that the FOS is 0.979, as shown in Fig. 6. The output indicates that the existing condition slope does not meet the minimum FOS of 1.300 for an untreated slope. According to guidelines, all untreated slopes, either cut slopes, fill slopes or embankments, shall be designed with a minimum FOS of 1.300, while treated slopes must have a minimum global FOS of 1.500. The result clearly classifies the slope as unstable, implying a considerable risk of failure if no intervention is implemented. These findings underscore the urgent need for a suitable remedial strategy to increase the safety margin and ensure the long-term stability of the slope.

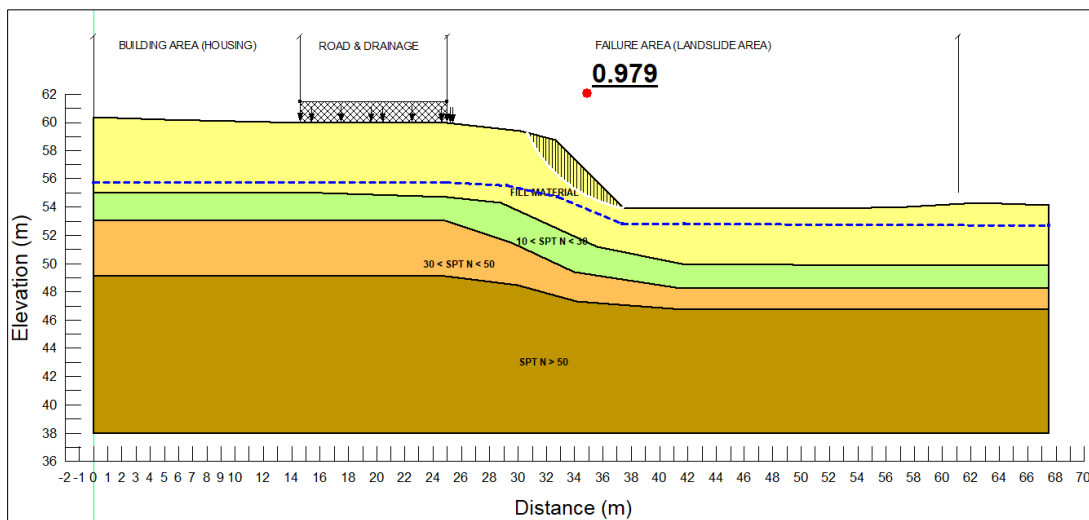


Fig. 6 The cross-section A-A' with existing condition of stability with FOS = 0.979

Following the implementation of the proposed remedial measure employing the WTFGS, a comprehensive slope stability analysis was conducted to assess its effectiveness in enhancing the FOS. As illustrated in Fig. 7, the limit equilibrium method (LEM) analysis using the Morgenstern-Price method within the SLOPE/W software produced a global FOS value of 1.580. This value surpasses the minimum required threshold of 1.500 for treated slopes, as stipulated by the Slope Guidelines published by the Public Works Department Malaysia version 2010. The marked improvement from the untreated condition (FOS = 0.979) highlights the positive impact of the WTFGS in reinforcing slope stability. The findings validate the suitability of waste tire materials as an alternative construction medium within gabion structures, offering both geotechnical reliability and environmental benefits.

A comparative assessment of the slope stability analysis under existing and remedial conditions clearly illustrates the effectiveness of the proposed WTFGS as a sustainable remediation technique. The analysis of the existing slope condition revealed a FOS of 0.979, which falls below the minimum recommended threshold of 1.300, indicating an unstable slope with a high potential for failure under static loading conditions. In contrast, the implementation of the WTFGS in the slope model significantly improved the slope's stability, resulting in a calculated FOS of 1.580. This improvement not only satisfies the standard geotechnical safety criteria but also demonstrates the structural contribution of the recycled waste tire-filled gabion structure in enhancing shear resistance and reducing failure potential. Studies by Apriyono *et al.* [50] have shown that woven waste tires exhibit impressive tensile properties, which are critical for the stability and durability of gabion structures.

Additionally, when integrated into gabion wall systems, it can enhance the overall mechanical performance of the walls by providing added resistance against deformation and enhancing the structure's load-bearing capacity. The results validate the use of WTFGS as a technically viable and environmentally responsible solution for slope rehabilitation, particularly in areas prone to landslides. This comparative outcome emphasises the importance of incorporating innovative materials and detailed geotechnical analysis in designing remedial strategies for unstable slopes.

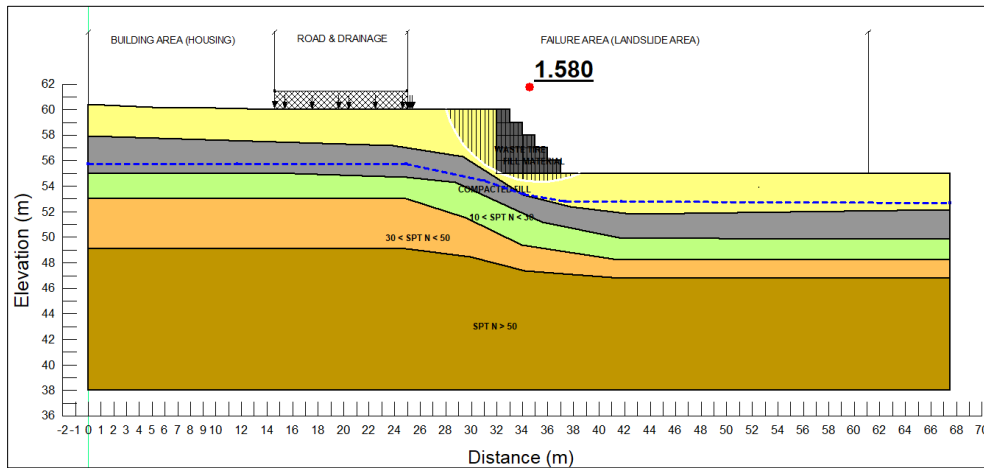


Fig. 7 The cross-section A-A' with proposed remediation by WTFGS analysis with FOS=1.580

The graphical comparison of slope stability under both existing and remedial conditions illustrates a significant improvement in FOS following the implementation of the WTFGS, as depicted in Fig. 8. Under the existing condition, the slope's FOS was recorded at 0.979, as shown in the graph, falling well below the generally accepted minimum threshold of 1.300. These clearly indicate an unstable slope prone to failure, which correlates with the observed signs of distress in the field. In contrast, the remedial condition demonstrates a marked increase in FOS to 1.580 after the application of WTFGS. The improved FOS was 1.50, as depicted in the comparison graph, which reflects the effectiveness of the WTFGS in mobilising additional resistance through enhanced confinement and frictional interaction between the waste tires and the surrounding soil. Therefore, this side-by-side graphical analysis provides compelling evidence that the WTFGS not only stabilises the slope but also offers a sustainable and resilient alternative for landslide-prone areas.

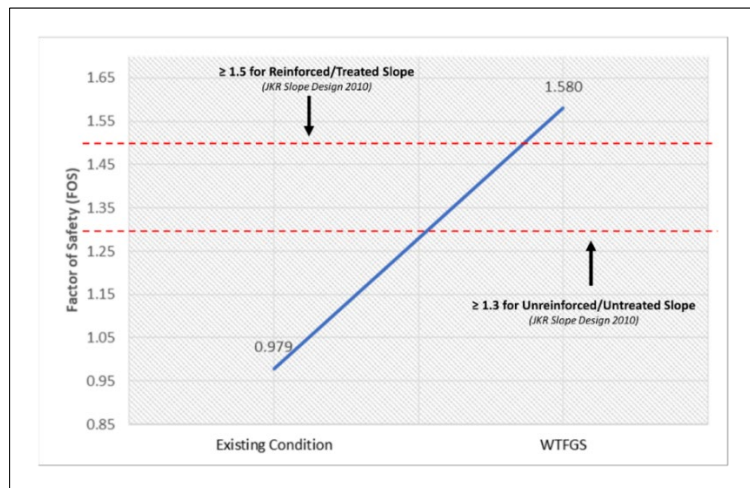


Fig. 8 Comparison of FOS between both existing and remediation condition

4. Conclusion

This study successfully demonstrated the comprehensive forensic investigation and geotechnical modelling of a landslide disaster and associated slope failure that adversely affected nearby infrastructure. The slope failure under investigation caused significant damage to nearby infrastructure, underscoring the importance of comprehensive site assessment and targeted remediation strategies. Through detailed geotechnical investigations, laboratory testing, and numerical modelling using SLOPE/W software confirmed that the existing slope condition, with a Factor of Safety (FOS) of 0.979, falls below the acceptable stability threshold, thereby indicating the need for immediate remedial intervention. The proposed remediation strategy employing a waste tire-filled gabion structure (WTFGS) significantly improved slope stability, yielding a post-remediation FOS of 1.580, in compliance with standard geotechnical guidelines. This outcome validates the structural viability of WTFGS and underscores its potential as a sustainable, cost-effective solution for slope stabilization. The findings

advocate for the broader adoption of recycled materials such as waste tires in geotechnical engineering, contributing to environmental conservation and the resilience of critical infrastructure. However, further research is necessary to ensure optimal use of this method and guarantee its widespread and large-scale use. In addition, it is necessary to evaluate long-term performance levels and address concerns about environmental pollution, such as the generation of leachate from tire physical deterioration. This comprehensive strategy can demonstrate success in sustainable construction, maintenance, and repair and thus address the increasingly critical issue of waste management.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. No financial interests, personal relationships, or affiliations influenced or could be perceived to have influenced the work reported in this study. All authors have disclosed any potential competing interests and affirm that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Author Contribution

The authors confirm contribution to the paper as follows: **conceptualization, methodology, writing-origial draft preparation:** Solahuddin Daud; **data collection:** Mohd Fakhrurrazi Ishak, Solahuddin Daud, Qistina Hannah Hussein; **analysis and interpretation of results:** Solahuddin Daud; **draft manuscript preparation:** Solahuddin Daud, Qistina Hannah Hussein. All authors reviewed the results and approved the final version of the manuscript.

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