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Enhancement of Structural Integrity on Apron and Soil Settlement Behavior at Kompleks Penghulu Ayer Hitam, Muar Structures

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Abstract

Concrete apron failure, often linked to soil settlement, presents significant challenges in civil engineering and infrastructure development. This study investigates the mechanisms contributing to apron deterioration, including cracking, spalling, and structural instability, focusing on soil settlement behavior. Field studies and laboratory tests such as Atterberg limit, grain size analysis, compaction test, and consolidation tests were conducted. Results show the soil has a moderate plasticity index (9.9%), is well-graded gravel (Cu=3.75, Cc=1.5), with an optimum moisture content of 14.5% and a rapid consolidation coefficient (12.74 m²/year). These findings inform recommendations for improved apron designs. Geogrids are proposed as an effective solution to enhance stability and durability, addressing the complex interaction between soil and concrete structures.

1. Introduction

Buildings are key elements of an economy, significantly impacting living conditions [1]. Residential buildings offer various housing options to meet diverse needs and preferences, using materials such as wood, concrete, steel, and brick. Design must comply with zoning regulations and building codes to ensure safety and consistency. Layouts vary based on architectural styles, cultural preferences, and residents' needs. Structural integrity and safety require adherence to local laws and regulations, with stable foundations to withstand loads. Residential buildings consist of structural elements, which provide support and stability, and architectural elements, which enhance aesthetics. A primary issue with soil settlement in residential buildings is apron failure, resulting in visible damage due to soil movement.

2. Soil

Soil, the Earth's uppermost layer, comprises a mix of inorganic and organic particles and is vital for supporting agricultural plants by providing stability, water retention, and essential nutrients. Its chemical and physical characteristics vary due to processes like leaching, weathering, and microbial interactions, resulting in diverse soil types with different agricultural benefits and drawbacks.

Soil also reduces urban runoff through infiltration and nutrient attenuation [2]. In construction, soil significantly impacts structure design, stability, and performance. Prior to construction, site investigations are crucial to determine soil conditions and create a soil profile diagram, which identifies distinct soil layers (horizons) and their characteristics. Fig. 1 shows the soil profile diagram.
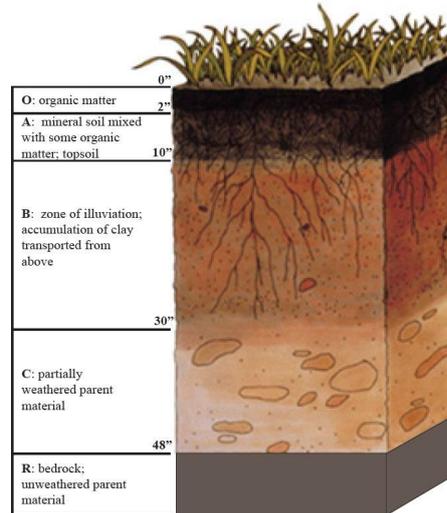
Fig. 1 *Soil profile diagram [2]*

2.1 Soil Settlement

Soil settlement, the process of soil consolidation beneath structures, causes sinking and can lead to cracks in foundations, slabs, masonry veneer, ceilings, and walls [3]. Settlement is often due to building on void-filled or poorly compacted soil. Heavy rain infiltrates soft soil, reducing its strength and causing subsidence as groundwater levels drop [4]. In Malaysia's wetland areas, soil settlement critically affects infrastructure like building aprons and retaining walls [5]. A special resin is injected to improve soil properties, as shown in figures depicting visible cracks and post-treatment results. Fig. 2 shows the result of before and after treatment.

(a) **(b)**

Fig. 2 *Result of before and after treatment (a) Before treatment; (b) After treatment [3]*

2.2 Effect of Soil Settlement

Soil settlement affects buildings through underground erosion, soil collapse, thermal changes, frost heave, vibrations, and shocks [6]. The most common effect is cracking, particularly shear cracks from uneven foundation settlement [7]. Cracks appear when settlement is uneven across a building [8] and are classified into non-structural and structural cracks.

2.2.1 Structural Cracks

Structural cracks, resulting from excessive loading, poor construction, and poor design, can pose serious safety hazards. These cracks may occur in beams, columns, slabs, and foundations and can appear as diagonal, vertical, or horizontal fissures. Structural fractures categorized into three types: slab cracks, column cracks, and beam cracks [9]. Table 1 shows the structural cracks forms on beam, column and slab. Fig. 3 shows the cracks on beam.

Table 1 *Structural cracks on beam, column and slab*

Beam	Column	Slab
Flexure cracks	Horizontal cracks	Flexure cracks
Shear cracks	Diagonal cracks	Shrinkage cracks
Torsional cracks	Corrosion cracks	Corrosion cracks
Combination of above cracks		
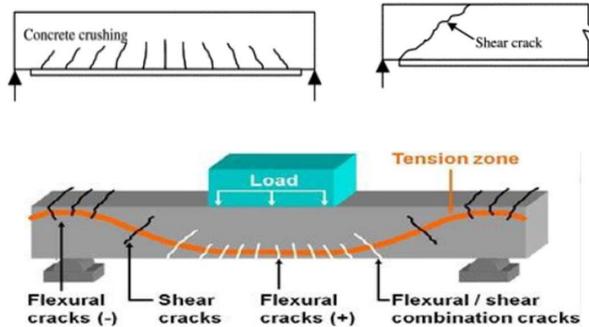
Fig. 3 *Cracks on beam [9]*

2.2.2 Non-structural Cracks

A foundation crack that is not threatening a building's structural integrity is known as a non-structural foundation crack. They are mostly caused by shrinking concrete during the curing process. Non-structural cracks are most found in finishes, partitions, or non-load-bearing elements. Fig. 4 shows the cracks in the building.

Fig. 4 *Cracks in the building*

2.3 Geogrids

Geogrids, geosynthetic materials used for reinforcement in construction, have become essential for reinforcing soil in both paved and unpaved roads with poor soil conditions [10]. Known for their high elasticity, geogrids effectively disperse loads across large surface areas. A junction in a geogrid is where longitudinal and transverse ribs meet, created through methods like knitting or weaving [10]. Fig. 5 illustrates the plan view of a geogrid section and labels its various components.
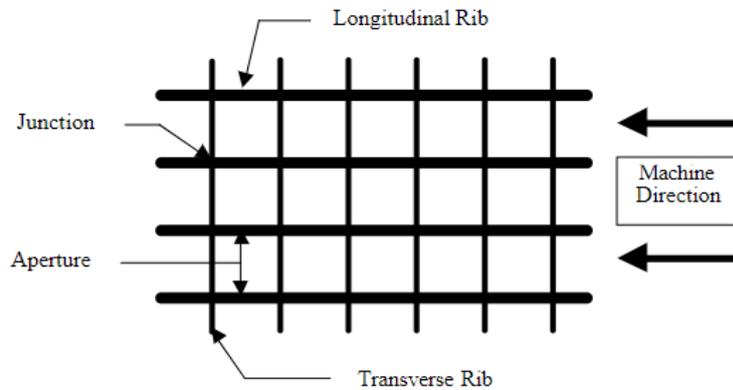

Fig. 5 *Geogrid component nomenclature*

Geotextiles prevent overlay cracking and serve as waterproof barriers, reducing vertical water flow into pavement structures [11]. Geogrids are classified into three types based on aperture: uniaxial, biaxial, and triaxial. Uniaxial geogrids, with tensile strength in one direction, are used to reinforce slopes, retaining walls, and embankments. Biaxial geogrids provide tensile strength in two directions and are used for pavements, railroads, and flexible pavements but lose strength under multi-directional stress [12]. Triaxial geogrids, with triangular apertures and three rib orientations, offer uniform tensile strength in all directions and improved soil particle-rib interaction [12]. Fig. 6 shows the three types of geogrids.
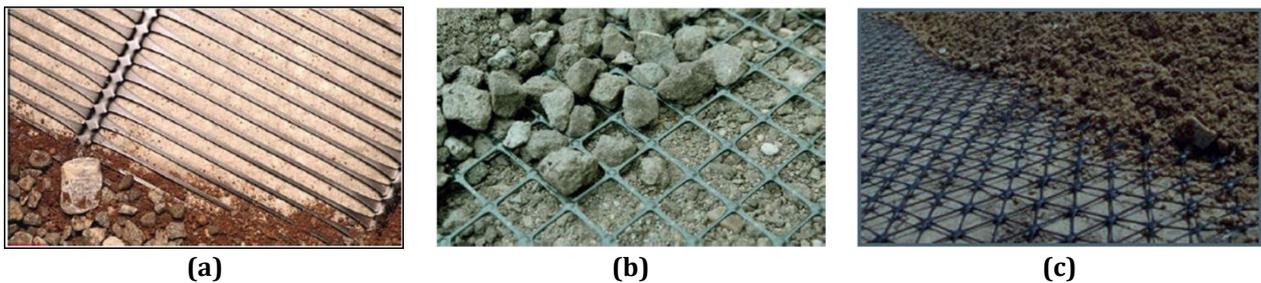

| **(a)** | **(b)** | **(c)** |

Fig. 6 *Types of geogrids (a) Uniaxial geogrids; (b) Biaxial geogrids; (c) Triaxial geogrids*

From a test, the ultimate load increases with each geogrid layer, reaching about 2.5 times that of the unreinforced sample with 5 layers of grid [13]. The more reinforcing layers there are, the less lateral bulging and vertical compression there is. Fig. 7 indicates the effect of geogrid layers in triaxial test.
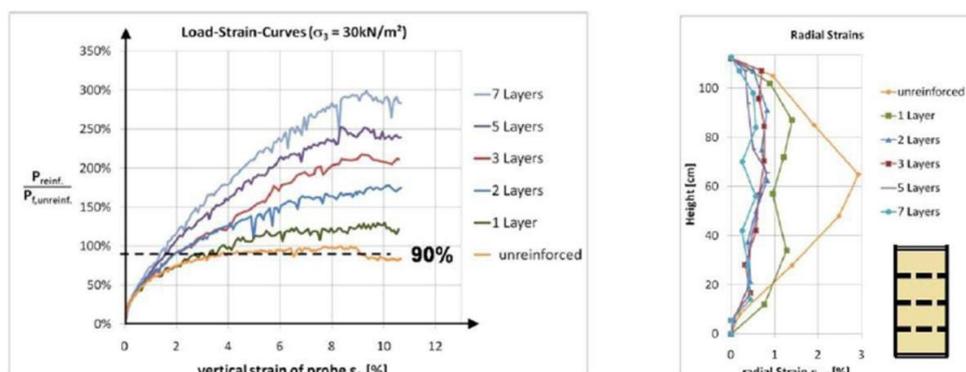
Fig. 7 *Effect of geogrid layers in a triaxial test*

3. Methodology

This investigation into concrete apron failure due to soil settlement employs a systematic methodology to explore the interplay between soil mechanics and structural integrity. Site investigations identified failure-prone locations, and soil samples were analyzed using Atterberg limit tests, grain size analysis, compaction tests, and consolidation tests to understand soil behavior. Based on the findings, mitigation strategies, including improved subgrade preparation, reinforcement techniques, and construction practice modifications, are proposed. This study aims to enhance understanding and provide effective engineering solutions to mitigate soil settlement impacts on concrete aprons.

3.1 Atterberg Limit Test

The Atterberg limits define water content thresholds where fine-grained soil transitions between different states: plastic to liquid or semi-solid to plastic [14]. These limits are assessed through three tests: shrinkage limit, plastic limit (PL), and liquid limit (LL). The tests help categorize soil based on plasticity and predict behavior under varying moisture conditions, crucial for construction and engineering. The Liquid Limit (LL) and Plastic Limit (PL) tests, guided by ASTM D4318 standards, determine the LL, PL, and Plasticity Index (PI) of cohesive soils. Fig. 8 shows the apparatus for Atterberg limit test.

The design and functionality of aprons are directly impacted by the Atterberg limits, which include the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI). Having a thorough grasp of soil behaviour under different moisture levels is essential. These limits aid in determining the soil's flexibility and its propensity for deformation or shrink-swell behaviour. Aprons may develop cracks and structural instability because of moisture fluctuations that cause differential settlement in soils with moderate plasticity (e.g., PI = 9.9%).

Atterberg limit tests (ASTM D4318) are used to evaluate the feasibility of soil for building and handle possible problems such as excessive deformation. If the soil exhibits undesirable plasticity, a stable and long-lasting apron structure can be ensured by applying stabilization techniques (such as cement or lime), proper compaction at the optimal moisture content (OMC), and geogrid reinforcement.
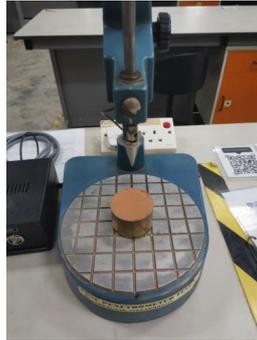

Fig. 8 *Cone penetrometer apparatus*

3.2 Grain Size Analysis

Grain size analysis is a key geotechnical engineering and soil science technique that characterizes the distribution of particle sizes in a soil sample. Engineering characteristics of the soil, including permeability, compressibility, and shear strength, are provided in the analysis. ASTM D6913: Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis are referred as guidance for this test. Fig. 9 shows the apparatus for grain size analysis.

Fig. 9 *Mechanical sieve*

3.3 Compaction Test

A compaction test is a common geotechnical procedure used to determine the optimal moisture content and maximum dry density of soil, essential for assessing its suitability for construction. Compaction increases soil dry density, reducing potential settlement under load and decreasing permeability [15]. This process involves applying stress to expel air from soil particles, enhancing the soil's engineering properties. It is a cost-effective and widely used soil improvement technique [16]. The Standard Proctor Compaction Test, following ASTM D698 guidelines, is the most frequently used method for evaluating compaction characteristics. Fig. 10 shows the equipment for compaction test.

Fig. 10 *Compaction test equipment*

3.4 Consolidation Test

A consolidation test is a geotechnical laboratory procedure that evaluates the compression and settlement behavior of soil under applied loads, providing critical data on soil response to stress changes and long-term settlement predictions. This test determines the compressibility and consolidation properties of soil. When a saturated, compressible clay layer is subjected to increased stress, the resulting pore water pressure gradually decreases over time [17]. The test follows ASTM D2435: Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading. Fig. 11 shows the apparatus for consolidation test.

Fig. 11 *Consolidation test apparatus*

4. Atterberg Limit Test Result

The Atterberg limit test measures soil's liquid limit (LL) and plastic limit (PL), providing information on the plasticity, compressibility, and behavior of fine-grained soils. Table 2 shows the result of water content and penetration from Atterberg limit tests, while Fig. 12 illustrates the LL of soils.

Table 2 *Results from Atterberg limit test*

Sample No.	1	2	3
Water content (%)	54.02	58.17	59.63
Penetration (mm)	14.4	23.3	27.8

Table 2 highlights the relationship between water content and penetration depth, demonstrating that higher moisture content leads to softer, less compact soil. Sample 1, with 54.02% water content and 14.4 mm penetration depth, indicates compact soil. Sample 2 (58.17% water content, 23.3 mm depth) and Sample 3 (59.63% water content, 27.8 mm depth) show increased softness and decreased compaction. Figure 12 indicates the LL of soil at 56.7%, the critical moisture content where soil transitions from a plastic to a liquid state under shear forces. This indicates moderate plasticity, important for geotechnical engineering.
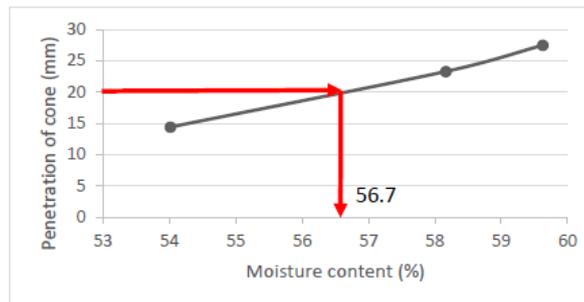

Fig. 12 *Liquid limit of soil*

Table 3 details the PL test results, identifying the moisture content at which soil transitions from plastic to semi-solid. This is crucial for determining the plasticity index (PI), which indicates the range of moisture content over which the soil remains plastic. A PI of 9.9% suggests moderate plasticity, indicating some moldability and deformation under pressure. High PL soils, which have more clay content, can significantly impact construction by affecting soil behavior, compaction, and foundation stability.

Table 3 *Plasticity index of soil*

Sample No.	1	2	3
Water content (%)	44.83	44.73	47.83
Plastic limit (%)		46.80	
Plasticity index = Liquid limit – Plastic limit = 9.9%			

4.1 Grain Size Analysis Result

Table 4 presents the results of a sieve analysis, a standard geotechnical test used to determine the particle size distribution of soil samples. The table lists sieve sizes, mass retained, mass passing, and percentage passing for each sieve. For the coarsest sieve (5.0 mm), all material (214.6 g) passes through, indicating 100% passage. This trend continues with decreasing sieve sizes. For example, the 1.18 mm sieve retains 21.1 g, with 90.2% passing through. The smallest sieve (0.063 mm) retains all particles (5.8 g), resulting in 0% passage.

Table 4 *Percentage passing for each sieve size*

Sieve size (mm)	Mass retained (g)	Mass passing (g)	Percentage passing (%)
5.0	0.0	214.6	100
2.0	0.0	214.6	100

1.18	21.1	193.5	90.2
0.60	28.6	164.9	76.8
0.425	37.8	127.1	59.2
0.300	48.1	79.0	36.8
0.212	52.3	26.7	12.4
0.150	20.9	5.8	2.7
0.063	5.8	0.0	0
Pan	0.0	0.0	0

Cu is determined as the ratio of particle diameter D_{60} to D_{10}, yielding a value of 3.75, indicating a wide range of particle sizes in the soil sample. The coefficient of gradation, Cc, results in a value of 1.5. The particle size distribution curve, shown in Fig. 13, illustrates these properties graphically, with percentage passing on the y-axis and grain size on the x-axis. The curve starts with 100% passage at the largest sieve size (5.0 mm) and gradually drops with decreasing particle size, reflecting the soil's gradation. Fig. 14 shows the Unified Soil Classification System (USCS) classification based on the test results, with the soil having a Cu of 3.75 and a Cc of 1.5.
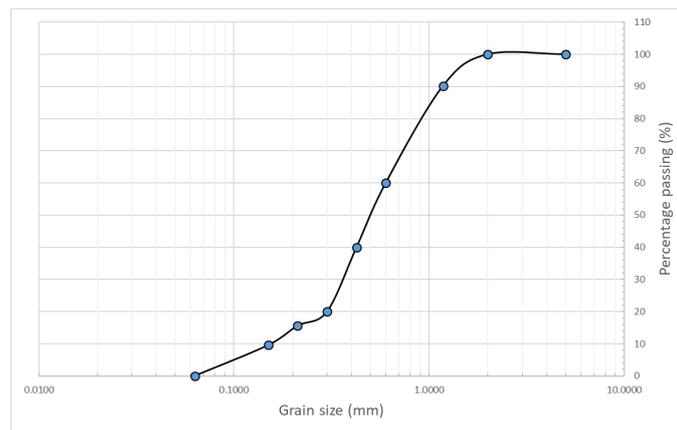

Fig. 13 *Particle size distribution curve*

Fig. 14 *Unified soil classification*

4.2 Compaction Test Result

The compaction test determines the Optimum Moisture Content (OMC) at which soil reaches maximum density during compaction. Using the Standard Proctor test, soil is compacted in three layers with 25 blows per layer. Table 5 shows that as moisture content increases, the dry unit weight of the soil increases up to a certain point,

forming a typical compaction curve. Initially, added water improves soil workability and compaction, increasing density. However, beyond the OMC, excess moisture saturates the soil, making it too soft and less compactable, thus decreasing density.

Table 5 *Compaction test results*

Sample test	1	2	3	4	5
Moisture content (%)	8.23	11.4	15.0	22.0	26.05
Dry unit weight (g/cm³)	7.58	8.53	8.85	8.20	7.81

Fig. 15 shows the compaction curve, indicating the optimum moisture content (OMC) of soil at 14.5%. This OMC represents the moisture level at which the soil achieves its maximum density during compaction. At 14.5% moisture, soil particles rearrange effectively, yielding the highest possible density under compaction. However, for well-graded gravel, an OMC of 14.5% is considered high, resulting in lower density and increased softness, leading to potential settlement. Coarse-grained soils like gravel and sands typically have lower OMC values than fine-grained soils because they retain less water [5].
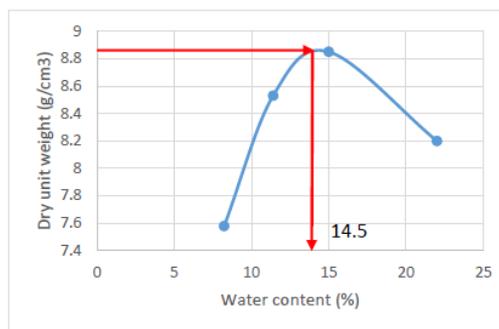

Fig. 15 *Compaction curve*

4.3 Consolidation Test Result

The consolidation test measures the volume loss of a laterally constrained soil specimen under vertical pressure. The resulting data allows for the calculation of the soil's compression index, recompression index, pre-consolidation pressure, and consolidation and secondary compression coefficients. Table 6 summarizes settlement observations at various time intervals. Initial settlement rates are high, indicating rapid deformation. Over time, the settlement rate stabilizes, with changes becoming less pronounced, indicating increasing material stability. Settlement continues due to secondary consolidation over extended periods [18]. Settlement values range from 0.85 mm to 1.637 mm, reflecting the degree of deformation. Tables 6 shows the consolidation test data. Fig. 16 illustrates a T_{50} value of 0.75 minutes, indicating that the soil achieves 50% primary consolidation quickly, demonstrating strong permeability and effective water drainage. This rapid consolidation is crucial for geotechnical engineering and construction.

Table 6 *Data results from consolidation test*

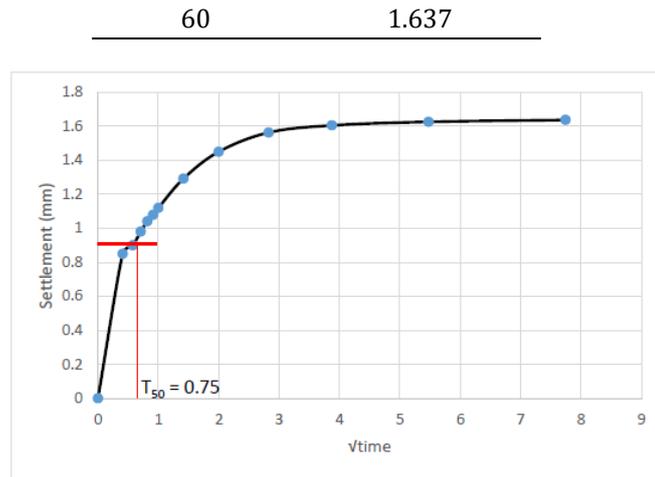| Time (min)	Settlement (mm)
0	0
0.17	0.85
0.33	0.90
0.50	0.98
0.67	1.041
0.83	1.078
1	1.119
2	1.291
4	1.450
8	1.563
15	1.605
30	1.626

Fig. 16 *Consolidation curve*

$$C_V = \frac{T_v H^2}{t} = \frac{0.197 \times (19.28/2)^2}{0.75} = 12.74 \ m^2/year \tag{1}$$

The coefficient of consolidation (Cv) of 12.74 m2/year shows that soil consolidates quickly under load conditions. In geotechnical engineering, this value is vital since it provides information about how the soil settles. Understanding Cv helps to build foundations and structures that can endure expected settlement, assuring long-term stability and safety.

5. Conclusion

The analysis highlights several crucial soil properties relevant to geotechnical engineering. A plasticity index (PI) of 9.9% indicates moderate plasticity, critical for assessing load behavior and suitability for construction projects. The uniformity coefficient (Cu) of 3.75 and coefficient of gradation (Cc) of 1.5 suggest well-graded soil with diverse particle sizes, offering robust strength, permeability, and compaction properties. The optimal moisture content (OMC) of 14.5% is the moisture level at which soil achieves maximum compaction density, guiding appropriate compaction techniques during construction. A coefficient of consolidation (Cv) of 12.74 m^2/year indicates rapid soil consolidation under stress, essential for predicting settlement and deformation of structures.

Despite generally suitable characteristics, the rapid consolidation (Cv = 12.74 m^2/year) poses a significant challenge for apron design, leading to uneven settlement and potential cracking. Geogrid reinforcement is recommended to enhance bearing capacity, reduce differential settling, and improve load distribution, ensuring a more resilient and stable apron. Further site-specific investigations and engineering analyses are necessary to confirm soil suitability and address potential risks.A major contributing factor to the apron failure is the high rate of soil consolidation (Cv = 12.74 m^2/year). resulting in unequal settlement when under load. Even with the soil's moderate flexibility (PI = 9.9%) and well-graded character (Cu = 3.75, Cc = 1.5), uneven settling would have been worse by inadequate compaction or moisture fluctuations. Structural instability and fracture caused by this uneven settling. Geogrid reinforcement is advised to improve load distribution, lower differential settlement, and increase bearing capacity in order to lessen these problems. The long-term durability of the apron depends on proper compaction at the ideal moisture content (OMC = 14.5%) and additional site research.

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Conflict of interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Darren Daniel Chin Vui Shiung, Tuan Norhayati Binti Tuan Chik; **data collection:** Darren Daniel Chin Vui Shiung; **analysis and interpretation of results:** Darren Daniel Chin Vui Shiung; **draft manuscript preparation:** Darren Daniel Chin Vui Shiung and Nor Athirah Farhah Binti Mat Jali. All authors reviewed the results and approved the final version of the manuscript.*

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