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ASSESSING THE RAPID DRAWDOWN RISKS ON SLOPE STABILITY

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Highlights:

- Review on drawdown effect on slope stability.
- Field investigation to confirm the causality of dewatering.
- Numerical modelling for assessing the factor of safety for proposed stabilisation methods.

Abstract: This study investigates the slope failure that occurred at a 152.18-acre residential development in Kulim. The unreinforced slope was reported to be deemed stable before its failure in the mid-April 2023. Continuous pumping activity for nearby basement construction had been underway for several weeks prior to the failure. To confirm the causality of drawdown effect, the groundwater level was monitored using two piezometer standpipes. The fieldwork investigation confirmed a significant difference in groundwater levels caused by the dewatering activities. By developing a numerical model using Slope/W software, slope stability analysis was performed to assess the slope performance before and after the failure, analysing the impact of dewatering. The findings revealed a significant reduction in the factor of safety (FOS) from 1.348 to 1.080, not adhering to the Jabatan Kerja Raya (JKR)'s slope specifications of a minimum FOS of 1.3 for unreinforced soil. The findings also confirmed the detrimental effect of rapid drawdown on the strength of the slope. To mitigate the slope failure, gabion walls were proposed as cost-effective alternatives. This remedial measure increased the FOS to 1.612, meeting JKR specifications of a minimum FOS of 1.5 for reinforced soil. The findings highlight the importance of educating on groundwater management to enhance safety and mitigate similar risks in future projects.

Keywords: Case Study, Drawdown, Factor of Safety, Kulim; Slope Stability; Numerical Model

1. Introduction

A residential development in Kulim, Kedah situated on a hilly terrain with 50m Reduced Level difference in topographical level has drawn attention to slope failure in mid-April 2023. During the site visit in May 2023, the project manager reported continuous dewatering operations for a nearby site's basement construction were underway a few weeks prior to the slope failure. A detailed location of the affected slope and location of dewatering activities close by to the residential development site is presented in **Figure 1**. The distance of the suspected activities and the affected slope is approximately 300m. To confirm the causality, a thorough forensic investigation works from a dewatering effect standpoint was carried out. The hypothesis of the study is due to the reduction of water due to dewatering causes shrinkage of the clay soil hence causing slope failure. This situation is due to the tropical climate of Malaysia which is caused by the infiltration of rainwater hence causing swelling and during the hot weather causes shrinkage of soil.

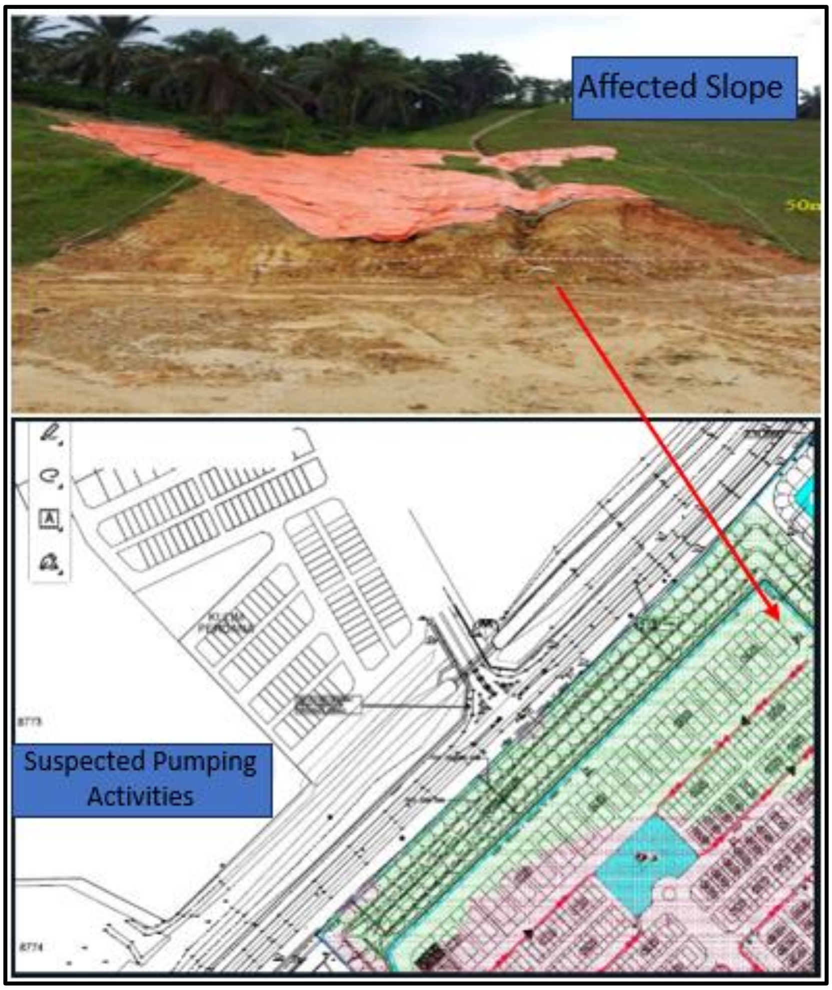

Figure 1. Affected slope and dewatering activity

2. Mechanism of Soil Distress Due to Dewatering

Soil distress resulting from dewatering is a major problem, especially in urban building projects. Dewatering is the process of decreasing in the groundwater levels due to multiple factors (Pinyol et al., 2008). According to Sew & Tan (2006), some of the factors are to facilitate construction operations ease, such as basement construction or excavation. This process causes the soil to undergo several mechanical changes, most notably consolidation and a rise in effective stress, which can result in higher risk of landslide failure, settlement and structural damage.

The process begins with the removal of pore water due to the lowering of the water table as seen in example **Figure 2**, in result it raises the effective stress of the soil and lowers pore water pressure. Volumetric decrease or settling results from the rearranging and compacting of soil particles brought on by this increase in tension, these rearranging can cause slippage between particles. In cohesive soils like clays and silts, which are prone to substantial shrinkage and breaking when desaturated, such settling can be especially troublesome (Hasan et al., 2023).

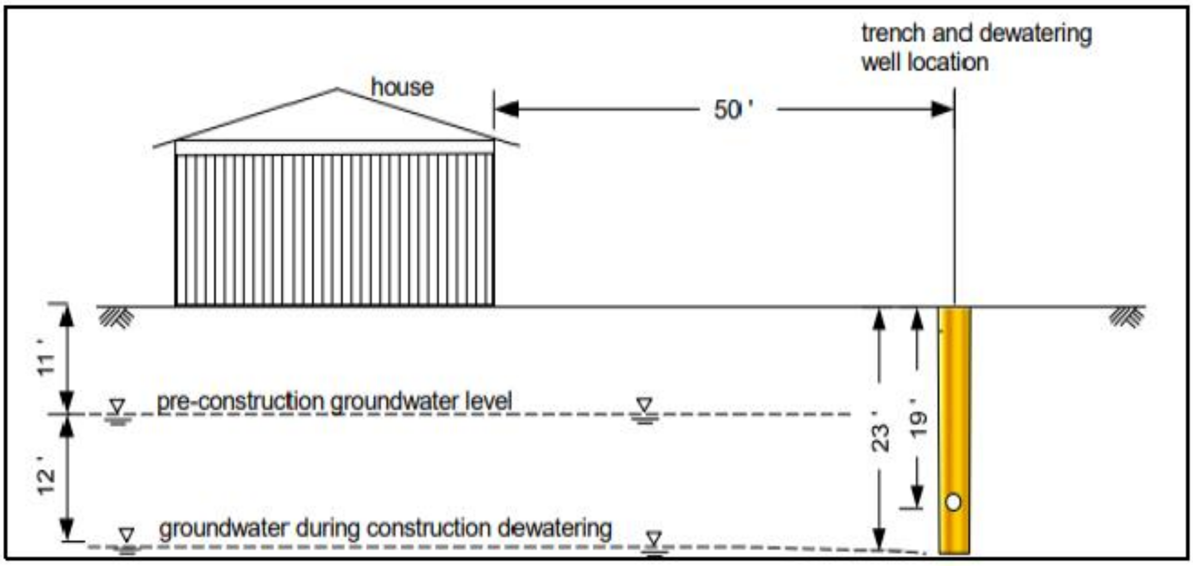

Figure 2. Lowering of ground water table during construction (Mowka, et al., 2011)

Differential settlement, where varying rates of consolidation occur across a slope, can exacerbate instability, leading to uneven ground surfaces and increased shear stresses. According to Wang (2020), this is particularly problematic in heterogeneous soil conditions or where soil layers have varying compressibility. Fine-grained soils, when dried, may exhibit fissuring and a loss of cohesion, further compromising slope integrity.

3. Methodological Approach

This study takes a systematic approach driven by forensic geotechnical investigation to break down all possible causality of slope failure, providing critical information for effective decision-making and effective mitigation solutions (Liew, 2017). The typical steps taken during a forensic geotechnical investigation are seen in **Figure 3.**

3.1 Framework for the Slope Stability Investigation

This study takes a systematic approach driven by forensic geotechnical investigation to break down all possible causality of slope failure, providing critical information for effective decision-making and effective mitigation solutions. **Figure 4** illustrates the framework for the slope stability investigation, showing the sequential progression of the actions required in conforming the causality of the slope failure.

3.2 Desk Study on the Affected Slope

The proposed development involves the construction of high-rise residential buildings in close proximity to the Kulim Hi-Tech Industrial Zone. The site is flanked by Taman Kulim Perdana and Kulim Perdana and is easily accessible via the Perdana Highway. The terrain is hilly, with a topographical variation of approximately 50m as seen in **Figure *5***, as indicated by the survey levels. The total land area spans 152.18 acres and includes two existing ponds. The adjacent developments consist of residential and industrial projects. Currently, there are no existing structures on the slope where the failure occurred.

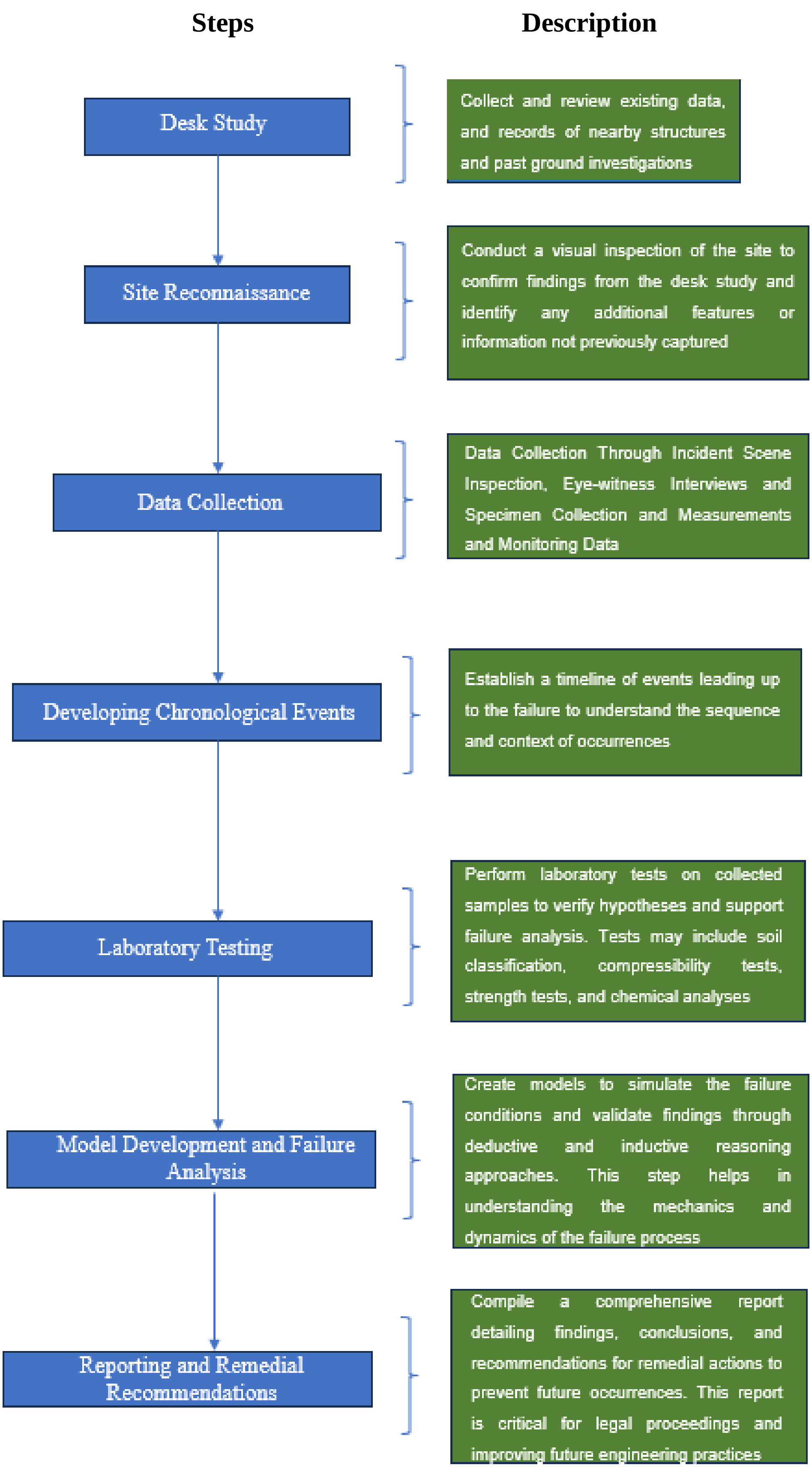

Figure 3. Geotechnical investigation steps (Liew, 2017)

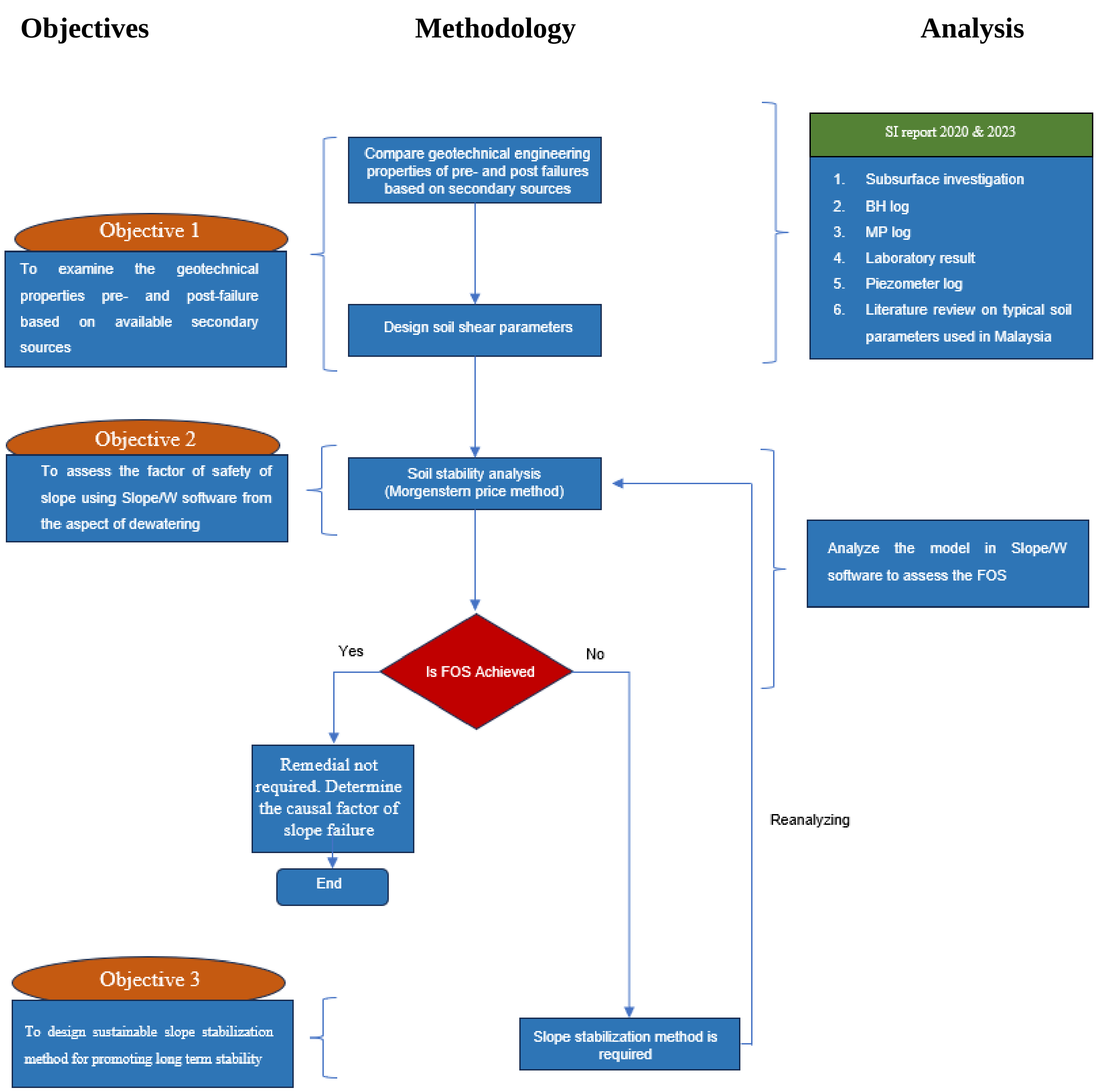

Figure 4. Research methodology flowchart

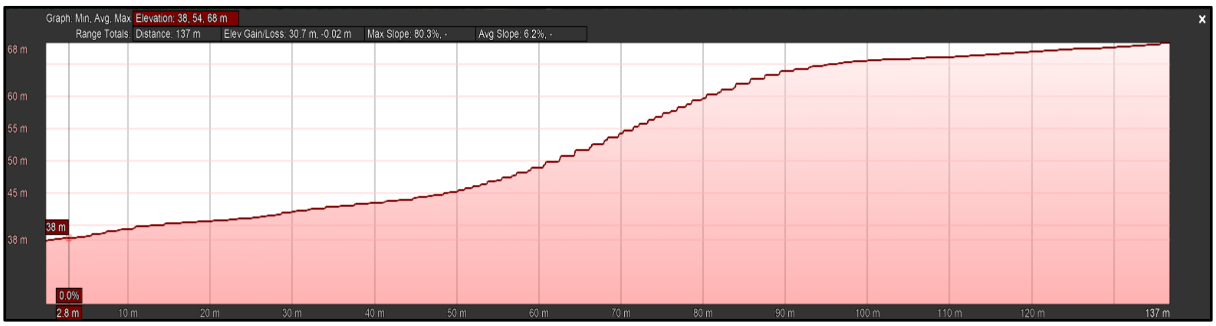

Figure 5. Cross section of slope failure

3.3 Soil Investigation

The SI work was conducted in April 2020 by a competent soil investigation contractor. The scope of SI works that was conducted are as follows:

i. 8 Boreholes (BH),
ii. 45 Mackintosh Probe Test (MP),
iii. 4 Standpipe Piezometer log (SP), and
iv. Laboratory test

Based on the SI mapping in **Figure 6**, the existing soil data of the site at the affected slope close by to BH3 is reviewed to understand its general subsoil profile.

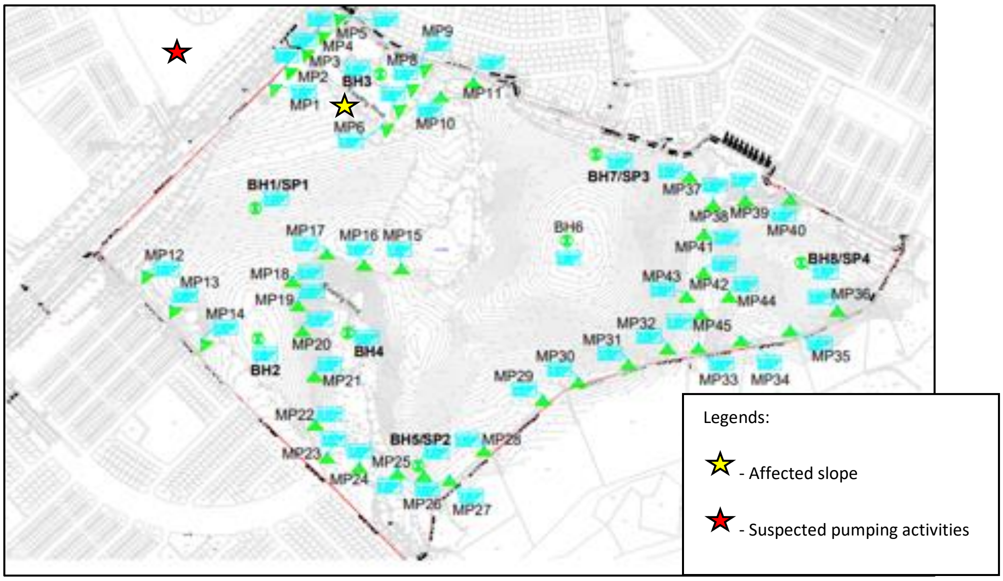

Figure 6. Set up of new standpipes after the slope failure

Based on the BH 3 soil data, three layers of subsoil layering were identified with no bedrock encountered at the affected slope area. The original groundwater from the closest SP1 monitoring to the affected slope was encountered at 6.2m below the ground level. The soil engineering parameters were analysed based on the prior laboratory works, including Triaxial Compression Test (CIU) and Direct Shear Box Test. Therefore, the adopted soil data for the numerical analysis is as follows in **Table 1**.

Table 1. Summary of soil properties obtained from triaxial test

Soil Layer	Cohesion, C' (Kpa)	Friction Angle, ϕ' (°)	Unit Weight, γ' (kN/m^3)
Layer 1	2	31	18
Layer 2	3	34	19
Layer 3	5	36	20

3.4 Data Review on New Soil Investigation (SI) Report 2023

Following the slope failure incident, an additional field examination was conducted in April 2023, by setting up two (2) new standpipe piezometers (SP) to confirm the lowering of groundwater levels. These SPs were deployed along the damaged slope that is close by to BH3 and at the likely pumping site, as shown in **Figure 7**.

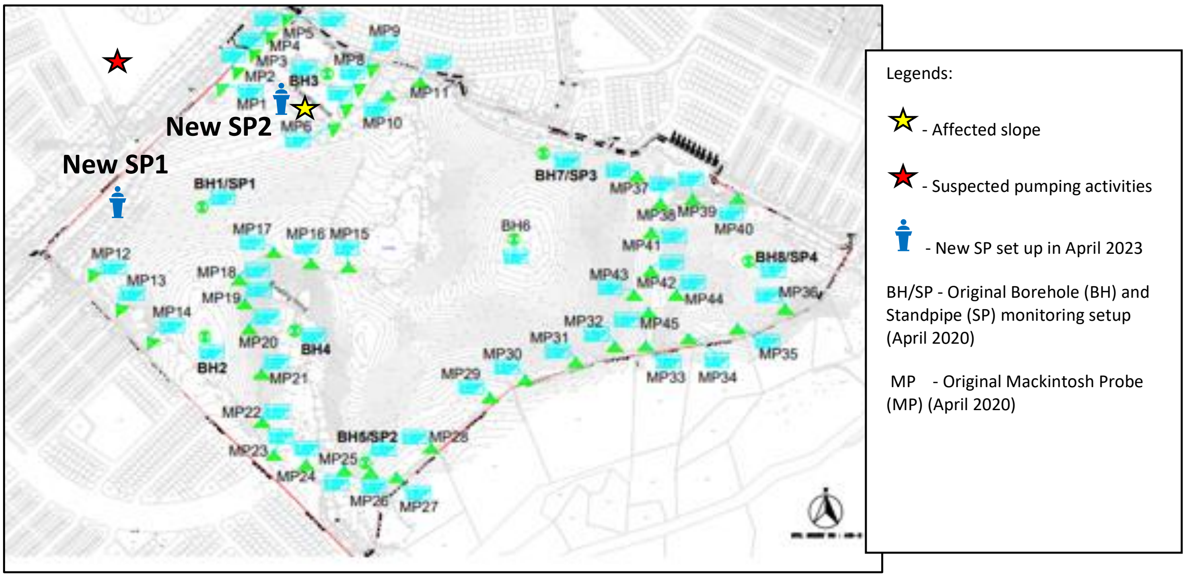

Figure 7. Original and new soil investigation works

Based on the monitored results of the newly installed standpipes, both standpipes conform the lowering of groundwater level up to around 14.25m below the ground level. To further confirm the significance of the effect of the differences between the original and new groundwater level on the slope, numerical investigations based on slope stability analysis were conducted to evaluate the factor of safety of the slope. The adopted soil data for the numerical analysis is the same as the original ground condition data**.**

3.5 Slope Stability Analysis

The slope stability analysis was carried out to confirm the causality of dewatering. The software opted is Slope/W Version 2018 R2. The software conducts the analysis in LEM method. According to Fan et al (2021), Morgenstern-Price method's emphasis on moment equilibrium enables a strong evaluation by capturing the various interactions that lead to slope stability. The Morgenstern-Price technique, which delves into the complexities of the static equilibrium differential equation, not only provides a strict framework for stability calculations, but also offers vital insights on the dynamic behaviour of slopes. The Morgenstern-Price method also as compared to the other methods places no restriction on the shape of the failure surface. To estimate future development that might happen on the slope, a surcharge of 10 Kpa is placed on the slope.

Based on the software simulation, the Factor of Safety (FOS) were assessed and compared to the FOS specification in **Table 2**, as guided by Jabatan Kerja Raya (JKR). Reinforcement design and analysis are necessary if the FOS was not reached in accordance with JKR's criteria. The recommended remediation solution for the slope under study should be carefully chosen based on the severity of the slope failure and the FOS received (Geostudio, 2020).

Table 2. JKR guidelines for reinforced and unreinforced slope design (JKR, 2010)

Design Components		**Mode of Failure**	**Minimum Factor of Safety**
Slope/Embankment (not on soft ground)	Unreinforced	1.1 Local & Global Stability 1.2 Bearing (Fill)	1.3 2.0
	Reinforced or Treated	1.3 Local & Global Stability 1.4 Bearing (fill)	1.5 2.0

4. Results of Slope Stability Analysis

4.1 For Original Slope Condition

In assessing the original slope condition, a surcharge was deliberately omitted to ascertain the factor of safety (FOS) of the slope in its natural state. This approach is essential to understand the inherent stability of the slope without additional loads or modifications. By evaluating the FOS under these circumstances, engineers can establish a baseline measure of the slope's safety and identify any underlying risks or weaknesses. Hence based on the analysis conducted the FOS of the slope is 1.348 as seen in **Figure 8**.

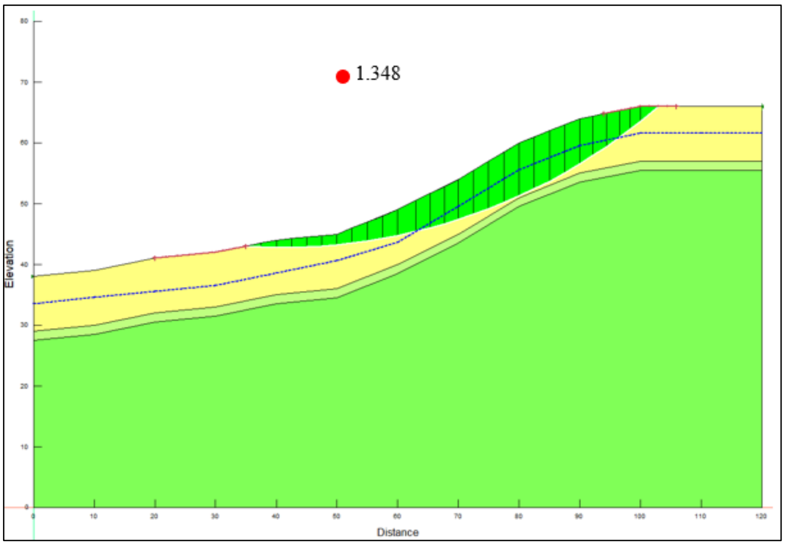

Figure 8. Factor of safety of original ground condition

4.2 For Affected Slope Condition

Following the slope failure, a comprehensive assessment was carried out to uncover the root causes. The slope is then modelled based on the before drawdown and after water level which is obtained from the piezometric data's. Surcharge of 10 kPa is then added to simulate in the event a development is to occur on top of the slope. Hence, once the parameters have been established, the data is placed in the Slope/W software and the Factor of Safety (FOS) of 1.080 once the reduction in water level is obtained as seen in **Figure 9.**

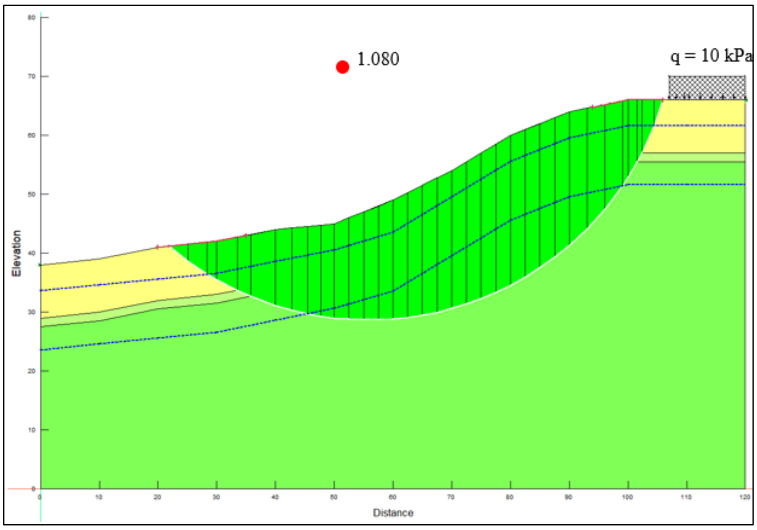

Figure 9. Factor of safety value with drawdown

4.3 Remedial Slope Stabilisation using Gabion Wall

Based on the slope stability analysis that was conducted after the rapid drawdown occurred, the Factor of Safety (FOS) that was obtained is 1.080. Based on the reading of the safety factor, it can be observed that the FOS is much lower than the FOS that is proposed by Jabatan Kerja Raya of 1.3. For this study, a one-tier gabion wall was installed at the point of the slope failure. Moreover, once the slope gabion wall has been installed, the back of the gabion wall is then cut to allow for a suitable soil backfill. Hence, the summary of the proposed design can be seen in **Table 3** and the FOS of the slope obtained from Slope/W is 1.612 as seen in **Figure 10**.

Table 3. Summary of proposed design used for slope

Slope Remedial Using Gabion Wall and Slope Cutting	
Gabion Tier	One - tier
Number of Berm	4 Berm
Factor of Safety (FOS)	1.612

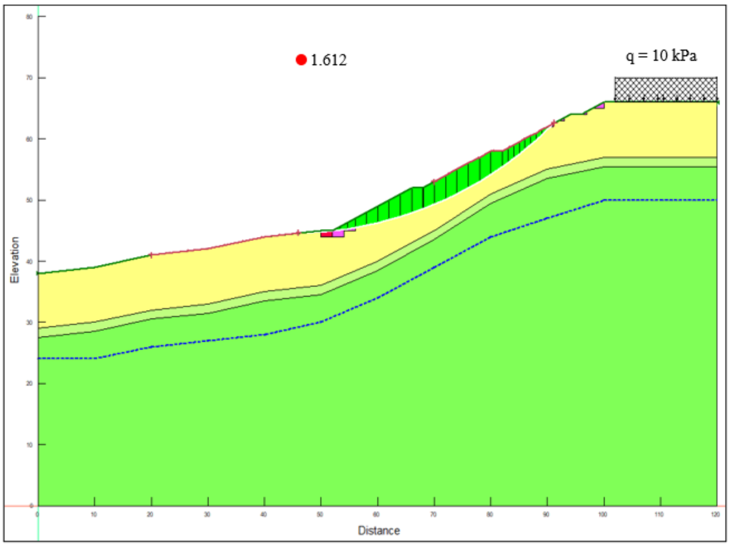

Figure 10. Factor of safety FOS for slope stabilization using gabion wall and slope

4.4 Remedial Slope Stabilisation using Soil Nailing

An effective and tried-and-true method for building excavations and stabilizing slopes is soil nailing. This can be accomplished by using relatively tiny, totally bonded inclusions typically steel bars to reinforce the ground in place (Jewell & Bruce, 1986). In this study, five soil nails, each measuring 12m in length, are used to anchor the failing slope, which has a Factor of Safety (FOS) of 1.080. As shown in **Figure 11**, the nails are positioned at a 25° inclination from the horizontal, with 1.5 m between each nail in the horizontal direction and 2 m between each nail in the vertical direction.

In addition, the slope undergoes a cut and fill procedure to guarantee that it satisfies the JKR standard, which stipulates that a fill slope's gradient must be 1H:2V. As a result, the FOS of 1.669 was achieved by completing the corrective in the slope/W program. This demonstrates that the slope conforms to the FOS of Jabatan Kerja Raya (JKR). The planned slope's design is summarized up in **Table 4**.

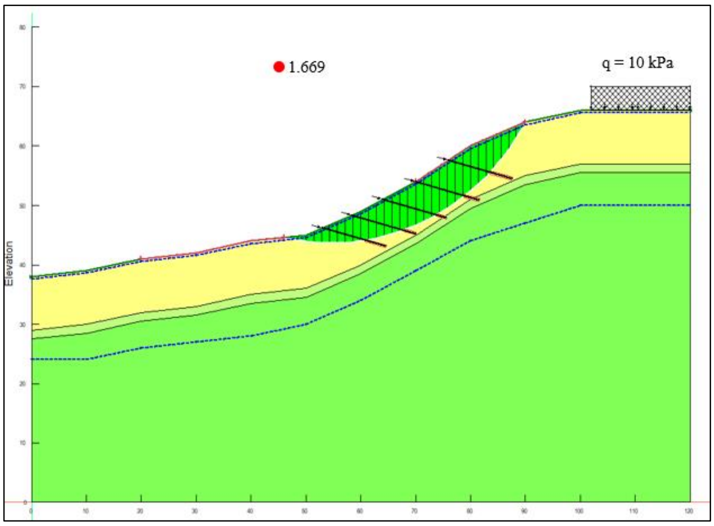

Figure 11. Slope stabilization using soil nailing

Table 4. Summary of proposed design used for slope

Slope Remedial Using Soil Nailing	
Number of Soil Nails	5
Length of Soil Nails	12m
Inclination Angle, °	25
Space between Soil Nail, Vertical	2.0m
Space between Soil Nail, Horizontal	1.5m
Factor of Safety (FOS)	1.669

5. Discussion of the Findings

As a framework for assessing slope stability, the Factor of Safety (FOS) becomes evident as a significant factor in geotechnical studies. The FOS offers a numerical assessment of its stability by contrasting the pushing and resisting forces acting on a slope. As seen in **Table 5** below, it is evident that the FOS of the untreated slope that is, the slope as it now exists gives a FOS of 1.080. The FOS does not comply with the specifications of the Jabatan Kerja Raya (JKR) standard, as was previously mentioned.

To increase slope stability, two different approaches are proposed: the use of gabion barriers and soil nailing, both of which are built using specific parameters according to the slope features. The Factor of Safety (FOS) for gabion walls is 1.612, whereas for soil nailing it is 1.669. Although the FOS values are almost identical, gabion barriers are chosen as the optimal corrective alternative because to their ease of on-site installation and low cost. Despite having similar stability results, gabion walls are a better alternative for controlling slope instability, ensuring efficient and cost-effective slope stabilization actions (Soheil Ghareh, 2015).

Table 5. The summary of FOS for untreated and treated slope based on JKR guidelines

Type of Slope	Factor of Safety (FOS)		JKR Guideline for Slope Design
Untreated	1.080		1.30
	Gabion Wall and Slope Cutting	Soil Nailing	
Treated	1.612	1.669	1.50

6. Limitation and Recommendation

The settlement of the slope was not addressed in this study. To ensure the long-term stability of slopes, future research should include an evaluation of settlement. Additionally, it is recommended that local authorities continuously update landslide hotspot data to facilitate easy tracking and improve hazard management. By incorporating settlement analysis and maintaining updated data, it can enhance the understanding of slope stability and develop more effective mitigation strategies. This proactive approach is crucial for preventing future landslides and ensuring the safety of communities living in vulnerable areas.

7. Conclusion

The aim of this study is achieved by identifying the elements that contribute to slope instability by proposing viable remedies through extensive investigation. The findings were made based on the research result and the discussion in which the research objectives and research question were answered. Several conclusions can be made based on the research carried out:

Two soil investigations conducted in 2020 and 2023 were thoroughly examined, revealing good soil strength with varying Soil Penetration Test (SPT) values across different depths. Groundwater levels measured using two SP indicated a significant drop from 5.53m to 15.52 m. The soil engineering parameters were analyzed for software simulation, successfully obtaining ground properties before and after failure, thus achieving Objective 1. Furthermore, based on the original ground conditions, the computed Factor of Safety (FOS) of the slope was 1.348, adhering to JKR guidelines (FOS > 1.3). However, the FOS drastically dropped to 1.080 due to rapid drawdown, highlighting increased instability and the slope's vulnerability. This deterioration necessitated remedial measures in line with JKR guidelines, achieving Objective 2. Moreover, the slope failures required reanalysis and the proposal of sustainable remedial measures to ensure stability. The proposed solution included installing a one-tier gabion wall and performing cut and fill procedures to achieve a 1H:2V gradient per JKR specifications. After implementing these measures, the FOS of the slope increased to 1.612, meeting the JKR specification of FOS > 1.5. This successful stabilization of the slope achieved Objective 3.

Conflicts of Interest

"The authors declare no conflict of interest."

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