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Influence of Rainfall Infiltration on Landfill Slope Stability

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Abstract: In Malaysia, slope failure is often caused by intense and prolonged rainfall. Commonly, the groundwater table in the affected areas has increased, and the ground faces erosion and runoff. Some Malaysian terrains are steep and hilly, increasing the risk of landslides. This scenario can result in significant consequences including loss of life, property damage, and environmental degradation. This study investigates the effect of rainfall infiltration on landfill slope stability using the finite element method (FEM) of Plaxis2D modeling. The study adopted the Mohr-Coulomb parameters and analyzed two main conditions: with and without rainfall infiltration. The behavior of landfill slope stability is determined by the generated pore water pressure. The highest pore-water pressure was 260.84 kPa at the slope toe. In addition, the safety factors were calculated for slope angles of 1:3, 1:4, and 1:5, yielding values of 2.237, 2.553, and 2.907, respectively. The slope of 1:5 represents the highest safety factor. The results show that rainfall infiltration dramatically reduces the safety factor, underlining the destabilizing effect on landfill slopes. Furthermore, the varying slope height, which is believed to be a crucial factor, was also studied. At steeper slope ratios, the slope is prone to failure. These findings provide an important understanding of the long-term stability of landfill slopes that are generally located in areas with heavy rainfall. This discussion provides valuable information for developing better risk assessment and mitigation strategies.

Keywords: landfill, slope stability, rainfall, safety factor

降雨渗透对垃圾填埋场边坡稳定性的影响

摘要：马来西亚的边坡崩塌通常是由强降雨和长时间降雨引起的。通常，受影响地区的地下水位会上升，地面也会面临侵蚀和径流。马来西亚的一些地形陡峭多山，这增加了发生山体滑坡的风险。这种情况可能导致严重后果，包括生命损失、财产损失和环境恶化。本研究使用 Plaxis2D 建模的有限元法（FEM）研究了降雨入渗对垃圾填埋场边坡稳定性的影响。该研究采用了 Mohr-Coulomb 参数，并分析了两种主要情况：有降雨入渗和无降雨入渗。垃圾填埋场边坡稳定性的行为由产生的孔隙水压力决定。坡脚处的最高孔隙水压力为 260.84 kPa。此外，还计算了坡度角为 1:3、1:4 和 1:5 的安全系数，得出的值分别为 2.237、2.553 和 2.907。 结果表明，1:5 的坡度代表最高的安全系数。结果表明，降雨渗透会大大降低安全系数，强调了对垃圾填埋场斜坡的不稳定影响。此外，还研究了变化的坡度高度，这被认为是一个关键因素。在更陡的坡度比下，斜坡容易发生故障。这些发现为了解垃圾填埋场斜坡的长期稳定性提供了重要的信息，垃圾填埋场斜坡通常位于降雨量大的地区。这一讨论为更好的风险评估和缓解策略提供了宝贵的信息。

关键词：垃圾填埋场，坡度稳定性，降雨，安全系数

1. Introduction

In the waste disposal process, landfilling is the main method and the most proposed option as the final receptor for Municipal Solid Waste (MSW), industrial waste, recycling waste, and sewage waste. Rapid global development has resulted in extensive waste production, especially in developed countries, leading to an increase in high-capacity landfills. Consequently, advances in research related to waste disposal have proven that landfill management as a bioreactor is a more sustainable waste management method [1].

In conventional landfills, waste is planted to slow biodegradation by reducing moisture pressure. For landfill, which is a bioreactor technology, the biodegradation process is accelerated by controlled input measures such as leachate recirculation, increased nutrient cycles, and increased bacterial populations [1]. Slope stability is an essential component of the construction and operation of landfills [2]. Slope failure is common in landfills with soft soil and high groundwater table levels [3].

Landfills were built and the garbage disposal process was designed to form a slope backfilled for coverage and monitoring over a 30-year period. Many parameters affect landfill slope stability [4], and the slope angle of a landfill is one of the most critical design parameters that determine the shape and capacity of a site. There are several obvious factors, such as slope stability, that regulate the maximum permissible interim and final slope angles, as well as the regulatory limits that affect the maximum slope geometry at the site. Steeper slopes increase the disposal capacity. Some countries regulate the maximum design steepness that can be constructed before deposition occurs, while there are also countries that allow slopes to be constructed greater than the design limit, permitting redeposition up to the maximum allowable slope [5].

Rainfall infiltration can have a significant impact on slope stability [6], particularly in the case of different rainfall patterns [7-9]. This impact is greater than that of other factors that result in landfill slope failure. Therefore, this study was conducted to investigate the influence of rainfall infiltration on landfill slope stability using a numerical method. This study is important because the rainfall distribution in Malaysia is high compared to that in other countries, which greatly affects the stability of slopes at landfills. Saturated slopes are prone to landslides, and landslide-supplemented slopes with varying shear strengths influence failure [10].

The aim of this study was to examine the influence of rainfall infiltration on landfill slopes using numerical modeling methods. The purpose of this study is to be implemented based on the following objectives: i) to identify safety factors for landfill slopes using numerical modeling methods, and to study the effect of rainfall infiltration on landfill slope behavior.

2. Waste at Landfills

With this fast-growing industry, waste generation has increased rapidly. Waste can be categorized into various forms, such as solids, sludges, liquids, and gases, as well as a mixture of them. Waste can be classified as hazardous or non-hazardous depending on the source of waste production. These hazardous and non-hazardous wastes can be classified into decomposed and non-decomposed groups. However, most waste generated in Malaysia is incinerated.

Waste is always disposed of in landfills. Today, 23,000 tons of waste is produced daily in Malaysia. Nevertheless, this amount is expected to increase to 30,000 tons per day by 2020 [11]. The amount of waste generated will continue to increase because of population growth and development, as well as when less than 5% of the waste is recycled [12].

End products that cannot be recycled, reduced, reused, or recycled will be disposed of in landfills. In Malaysia, landfilling is a more recommended approach than incineration because of its demographic characteristics. Landfills are places where waste cannot be reduced or recycled. Decisions regarding disposal depend on cost, soil availability, population characteristics, and proximity to water materials [13]. The area encompasses a large disposal area that contains many smaller cells and solid waste stored in these cells daily, using a specially designed bulldozer, and covered with a thin layer of soil or some alternative cover.

Moreover, there are a lot of unused former mine land and ponds that need to be replenished for development. Therefore, the Malaysian government prefers landfills over incineration. It can be found where landfills are rare and located in areas that are very far from the actual Municipal Solid Waste (MSW) generation center. Modern fuel gas combustion and purification methods render waste incineration an environmentally friendly method [7], [12].

Moreover, garbage disposal is widely recognized as the most suitable approach to waste disposal, rather than incineration. This process not only reduces the amount of waste and gaseous pollutants that require absolute disposal. Although solid waste disposal using landfills has been argued as a misnomer that hides grades under protection, it is still a common solution widely practiced in developing countries [14].

3. Landfill Models

This study was conducted using the Sungai Udang Landfill. Sungai Udang is a rapidly developing township located in Melaka. Its position is strategic, located between the differences between the main federation of Bandar Melaka and Masjid Tanah [15]. Sungai Udang is surrounded by several settlements such as Paya Rumput Jaya, Bertam Ulu, Pantai Kundor, and Tangga Batu.

The Sungai Udang Landfill was the chosen site for this study which located Sungai Udang - Paya Rumput - Ayer Keroh Highway (SPA), Sungai Udang, Melaka, Malaysia, with a waste capacity of 1200 tons/day. The landfill has been in operation for 3 years and has reached its maximum capacity. This study began with a literature review of previous studies and site visits. Once the data were obtained, eight models were modeled using Plaxis 2D software for 8 models. The obtained results were then compared and validated using a slope stability analysis.

3.1. Slope Geometry

All models with slope angles of 1:3, 1:4, and 1:5 were constructed to analyze the stability of the landfill slope at Sungai Udang, Melaka. The slope geometry with a total height of 40 m was divided into four layers, with a height of 10 m in each layer. All three models with slope angles were modeled using rainfall variables. The first three models were designed without rainfall, and the second model was simulated using infiltration data.

Among the three models, the best safety factors were selected to investigate the geometric changes in height (H = 15 m and H = 20 m). The geometry was based on the results of a landfill in Sungai Udang, Melaka, as shown in Figure 1. An example of a slope model with soil layers is shown in Figure 1 with a geometry of 1:3.

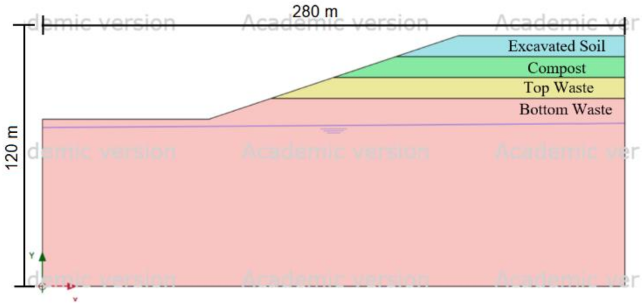

Figure 1. Slope model with soil layers (the authors' design)

3.2. Rainfall Intensity

Rainfall was a major variable in this project. Table 1 shows the total rainfall from the Malaysian Meteorological Department [16] for the State of Malacca from December 9, 2020, to December 22, 2020, consisting of a 14-day period. These rainfall data were used to simulate the slope stability in the presence of rainfall infiltration. It is important to include the data in the acceptable format of Plaxis; hence, the value of rainfall was converted from mm to m in units of m/day.

Table 1. Rainfall data for 14 days [16]

Days	Rainfall (mm)	Rainfall (m)
0	0.000000	0.000000
1	2.755493	0.027555
2	3.850845	0.038508
3	3.920704	0.039207
4	5.243803	0.052438
5	1.728592	0.017286
6	0.272958	0.002730
7	0.086056	0.000861
8	5.434789	0.054348
9	19.14169	0.191417
10	22.74028	0.227403
11	15.53732	0.155373
12	2.536479	0.025365
13	1.528451	0.015285
14	7.458451	0.074585

3.2. Material model and parameters

The Mohr-Coulomb model was used as the material model. The input parameters include the Young's modulus, Poisson's ratio, and void ratio. The models were assigned general fixities for the boundary conditions. The angular dilatancy was zero for all the layers.

Following the parameters of the Mohr-Coulomb model proposed by Omari [17], only four soil layers were considered in the numerical model by using the finite element method. Soil parameters were taken as waste comprising excavated soil, compost, top waste, and bottom waste. The soil parameters are listed in Table 2.

Table 2. Mohr-Coulomb soil parameters [17]

Parameter	Layers			
	Excavated soil	**Compost**	**Top Waste**	**Bottom Waste**
Dry Unit Weight, γ (kN/10^3)	7.40	6.81	9.40	11
Moist Unit Weight, γm (kN/10^3)	14.20	16.37	10.8	15.41
Young's Modulus, E (MPa)	5.0	5.0	1.0	2.5
Poisson's Ratio, V'	0.25	0.25	0.25	0.3
Cohesion, c'(kPa)	0	0	10	30
Friction Angle, θ (°)	32.70	18.28	30.00	20.00

The saturated hydraulic conductivity of soil ranges from 1 × 10 $^{-3}$ to 1 × 10 $^{-2}$ cm/s [18]. This indicates that most of the materials were highly permeable. As the density of waste increases owing to compression and sedimentation, its permeability can also decrease. Owing to the lack of field measurements available, the values from the literature review are deemed appropriate for use. Therefore, the permeability value used in this model is 1 × 10 $^{-3}$ cm/s.

4. Numerical Findings

A total of 8 different models with different geometric and parameter values were simulated in this study. The soil and material permeabilities of the models are fixed. In this section, we describe and discuss numerical findings based on the selected variables. Several studies have investigated these factors [19-21].

4.1. Generated Pore-Water Pressure

The pore-water pressure was measured 30 m from the crest and 30 m from the toe of the model. The results were captured with and without the phases of the rainfall events.

4.1.1 Slope Model without Rainfall

Figure 2 shows a graph of pore water pressure as a function of depth. Values from the graph were taken at the crests of the three models without rain at a depth of 30 m. The pore water pressure was measured in 5 m increments. The lowest values for the three models are at a depth of 0 m, which are -60.98, -60.89 kPa and -60.873 kPa. The highest values for the three models at a depth of 30 m are 28.45, 28.36, and 28.31 kPa. For the models with slope angles of 1:3, 1:4, and 1:5, it is shown that the increase in pore-water pressure when the height of the slope is larger and vice-versa with a reduction in pore-water pressure if the depth is kept constant.

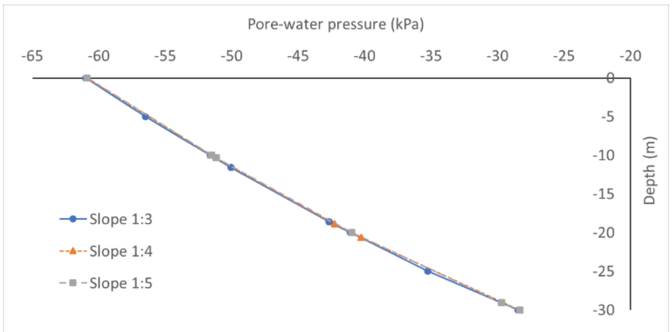

Figure 2. Graph of pore water pressure versus depth at the crest for models 1:3, 1:4, and 1:5

Figure 3 shows a graph of pore-water pressure against depth. Values from the graph were taken from the toes of the three models without rain at a depth of 30 m. The pore water pressure was measured for each 5-m increment. The lowest values for the three models were obtained at depths of 0 m (9.219, 5.116, and 6.492 kPa). The highest values for the three models were obtained at a depth of 30 m at 260.84 kPa, 260.26 kPa and 259.5

kPa. Models 1:3, 1:4, and 1:5 showed a high pore-water pressure increase when the slope depth was high. It can also be seen that the generated pore water pressure is nearly linear with slope depth.

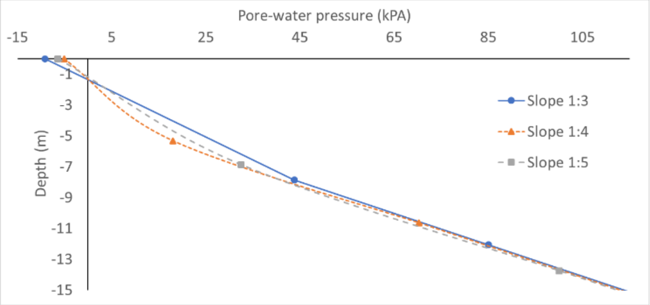

Figure 3. Graph of pore water pressure versus depth at the toe for models 1:3, 1:4, and 1:5 (developed by the authors)

4.1.2. Slope Model with Rainfall

In addition, Figure 4 shows a graph of pore-water pressure as a function of depth under the influence of rainfall. Values from the graphs were obtained at the crests of the three models with rainfall at a slope depth of 30 m. Next, the pore water pressures at each depth of 4 m were obtained. The lowest pore-water pressure in the 1:3 slope model was recorded at a depth of 5.03 m at 56.85 kPa. The lowest value for the 1:4 model was at a depth of 10 m, which was 53.33 kPa, whereas the 1:5 model with rainfall infiltration was significantly at the crest of the slope. Furthermore, the 1:3 slope model exhibits little difference in the value at a certain depth.

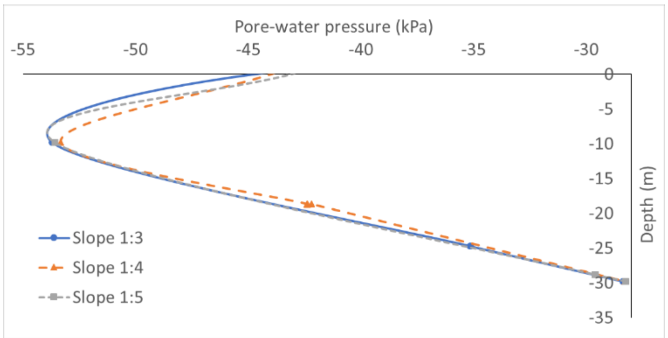

Figure 4. Graph of pore water pressure versus depth at the crest for models 1:3, 1:4, and 1:5 (developed by the authors)

Figure 5 shows the pore water pressure as a function of depth. Values from the graph were obtained at the feet of all three models with rainfall at 30 m depth. The pore water pressure at each 5-m increment was calculated. The lowest pore water pressures for the 1:2, 1:4, and 1:5 slope models were obtained at 0 m depths of 7.86, 10.84, and 8.117 kPa, respectively. The highest pore water pressure values for all the three models were obtained at a depth of 30 m, where the pore water pressure values were 261.66, 241.98, and 258.88 kPa. In Figure 4, models 1:3 and 1:5 show a uniform and linear decrease, while slope 1:4 shows an uneven decrease with a significant change in values at a depth of 5.32 m, whereas the other two models only have values of 44.612 kPa and 24.147 kPa, respectively. As also observed in [22], in slope models with different gradients, the highest pore water pressures occurred at the deepest levels.

Additionally, shallow slope damage caused by rainfall in hilly areas of tropical rainforests is a complex mechanical behavior that is difficult to analyze using conventional slope stability methods. The basic problem is the application of linear shear strength failures in cohesion bypass, where the shear strength is estimated to be too high at low-pressure levels, such as for effective pressures less than 100 kPa or for failures less than 5 m. At this low stress level, the pure rich strength behavior is not linear with zero cohesion [23].

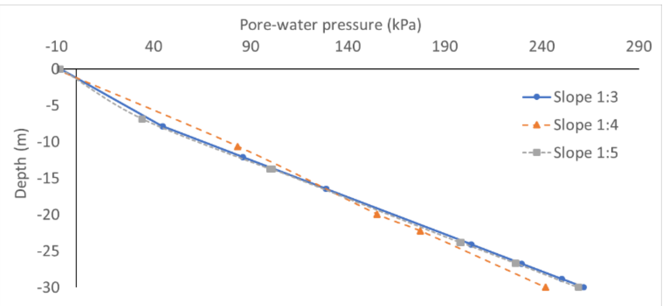

Figure 5. Graph of pore water pressure versus depth at the crest for models 1:3, 1:4, and 1:5 (developed by the authors)

4.2. Estimated Safety Factors

Three soil models with slope geometries of 1:3, 1:4, and 1:5 and different soil parameters according to the soil layer were excavated soil, compost soil, top waste, and bottom waste. The parameters for the modeling of each layer were the dry unit weight, moist unit weight, Young’s Modulus, Poisson’s ratio, cohesion, and friction angle. All parameters were based on the Mohr-Coulomb parameters with a 15-nod triangle element. The soil layers in all the models are shown in Figure 4.1.

4.2.1 Safety Factors for Model with and without Rainfall

The results of the slope stability analysis were performed on models 1:3, 1:4, and 1:5 with and without rainfall infiltration for 14 days.

A comparison of the safety factor values for the models with and without rainfall is shown in Figure 6.

Slopes without rain and slopes with rain showed increasing safety factors as the slope angle increased.

A decreasing safety factor value was observed for every model in the presence of rain. The safety factor of model 1:3 increased from 2.223 to 2.237, which may be due to simulation errors; the factor for model 1:4 decreased from 2.586 to 2.553, and the safety factor of model 1:5 also decreased from 2.921 to 2.901.

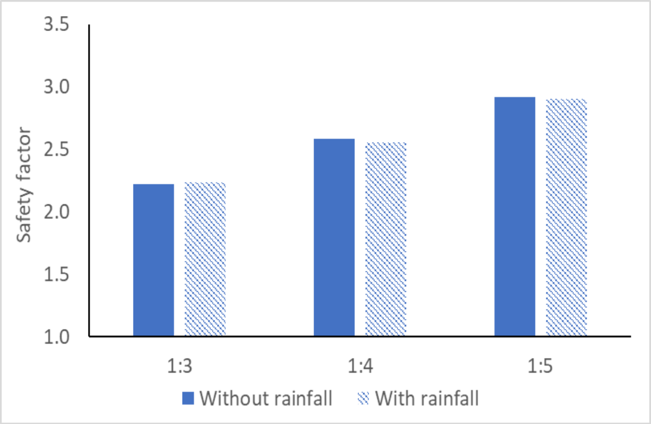

Figure 6. Graph safety factor versus slope model (by the authors)

All the models showed an insignificant change in the safety factor in the presence of rain. As also stated in [24], it was shown that with rainfall, the safety factor decreases as a result of reduced shear strength, thereby affecting slope stability.

4.2.2 Safety Factor for Model with different Heights

A slope model of 1:5 with rainfall that had the best safety factor was chosen, and another 2 models were formed. The first model had a depth of 15 m in each soil layer, whereas the other model had a depth of 20 m for every soil layer. The safety factors for both the models are compared in Figure 7.

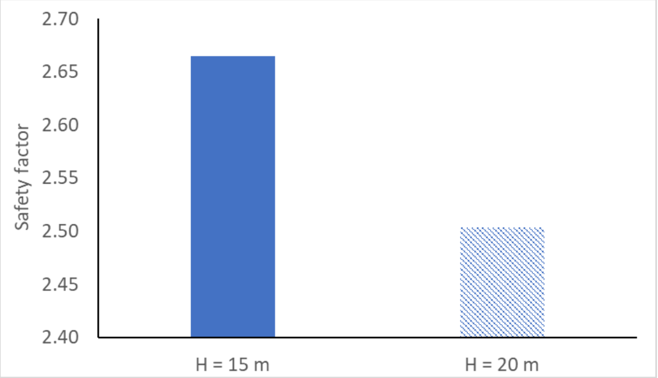

Figure 7. Graph safety factor against slope model 1:5 with H = 15 and H = 20 m (developed by the authors)

Figure 7 shows the model 1:5 with depths of 15 m and 20 m, which have safety factors of 2.655 and 2.504, respectively. The safety factor decreases as the height of each layer increases because if the height of the layer increases, the slope becomes steeper, which affects the stability of the slope owing to geometric factors. As also found in [25], the increased height and steeper slope angle create more driving forces that jeopardize slope stability, especially with rainfall infiltration, which increases the soil weight and reduces the shear strength.

5. Conclusion

This study was conducted to analyze the slope stability of landfills under the influence of rainfall infiltration using numerical modeling to determine the safety factor of the slope model. The main parameters of the landfill layer from the Mohr-Coulomb model are unit weight, Young's Modulus, Poisson's ratio, cohesion, and friction angle. The safety factor calculated using Plaxis 2D was directly proportional to the slope ratio. For slope models with ratios of 1:3, 1:4, and 1:5, the safety factors obtained from the modeling were 2.223, 2.586, and 2.921, respectively. This suggests that slope geometry plays an important role in determining the stability of landfills.

The slope of the landfill studied with rainfall infiltration is also directly proportional to the slope ratio. A reduction in the safety factor was discovered from the results compared to the safety factor of the slope without rainfall. The values for the 1:3, 1:4, and 1:5 models with rainfall were 2.237, 2.553, and 2.907, respectively. The occurrence of rain causes the generation of pore water pressure, thereby reducing the safety factor.

These findings highlight the impact of heavy rainfall on landfill slope stability and show that rainfall infiltration weakens soil pore water pressure. Steeper slopes are more prone to failure, whereas gentler gradients and proper drainage systems enhance the slope stability. This study provides key insights for improving risk assessment and designing effective strategies to mitigate slope failures in high-rainfall regions.

Declarations

Author Contributions

Conceptualization, N.N.N.; methodology, D.Z.A.H.; software, F.S.S.; validation, A.I.; investigation, N.N.N.; data curation, R.M.P.; writing—original draft preparation, N.N.N; writing—review and editing, A.M.T.; supervision, A.M.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript. In addition, ethical issues including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies were completely observed by the authors.

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