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BACK ANALYSIS OF RAINFALL-INDUCED WASTE DUMP FAILURE USING COUPLED HYDRO-MECHANICAL ANALYSIS – A CASE STUDY IN COAL MINE

*Barlian Dwinagara[1], Wahyu Nusantara Akbar[2], Singgih Saptono[3], Dahono Haryanto[4], Shofa Rijalul Haq[5], Prasodo Datu Prabandaru[6]

[1,3,4,5]Department of Mining Engineering, Universitas Pembangunan Nasional Veteran Yogyakarta, Indonesia; [2,6]PT Studio Mineral Batubara, Indonesia

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ABSTRACT: Managing the waste dumps has become a significant challenge, along with increasing mining production. Maintaining waste dump stability is vital to prevent failures that could lead to economic losses, environmental harm, and safety hazards. This study investigates the stability of waste dumps in open-pit coal mining operations, focusing on the impact of rainfall on dump stability. The objective was to evaluate a strain-based approach for predicting waste dump failures, accounting for changes in soil properties during rainfall events. A coupled hydro-mechanical framework was used to back-analyze the historical impact of rainfall on waste dump stability. The results showed strain values ranging from 2.79% to 7.36% during progressive slope failure. The weak nature of the waste dump material, with compressive strengths of less than 1 MPa and poor rock mass quality, enabled the development of an approximate maximum strain threshold graph. These findings could enhance predictive capabilities for waste dump stability and bridge the gap by utilizing coupled hydro-mechanical analysis, ultimately improving understanding and safety in waste dump operations.

Keywords: Coupled hydro-mechanical analysis, Waste dump failure, Back analysis, Open-pit coal mine

1. INTRODUCTION

Waste dump areas are the vital parts of open-pit mining that hold significant overburden material from coal mine excavation. These dumps can be placed internally within the mined-out area (in-pit dump) or outside it but within the leasehold area (out-pit dump). External dumps are less efficient compared to internal dumps. Despite this inefficiency, external dumping has the flexibility to choose more suitable sites. It could mitigate some adverse effects of mining operations but pose increased risks to social and environmental domains in case of failure. Managing the safe placement of extensive waste material within a limited dumping space is a significant challenge in open-pit mining. Over recent decades, numerous accidents caused by waste dump instability have been recorded, resulting in loss of life, production, and machinery and damage to nearby properties and the environment [1-4]. Destructive waste dump failures significantly disrupt mining operations and sometimes lead to mine closures.

Instability or failures in the waste dump area occur due to increased stress or decreased shear strength of the slope material. Approximately 90% of slope instability worldwide is mainly caused by rainfall-triggered failures [5, 6]. Rainfall-induced slope failures have often been reported to occur during, right after, or sometimes after an intense rainstorm or a long-duration rainfall with low intensity [7-9]. Rainfall infiltration causes an increase in the pore pressure and reduction of matric suction, subsequently reducing the shear strength of the material [10, 11], especially in soft material, i.e., a waste dump. The reduction in shear strength diminishes the resisting force, leading to a lower safety factor against slope instability [12]. More significant amounts of rainfall should allow slope movements to be activated, and prolonged rain can cause these movements to continue until failures occur [13, 14].

The interaction between rainfall and the mechanical stability of the waste dumps is critical for mitigating the failures. Understanding these dynamic interactions requires an integrated approach considering the hydraulic processes governing water infiltration and the mechanical responses influencing slope stability. Thus, a back analysis using a coupled hydro-mechanical analysis is an alternative approach to comprehending the rainfall-induced slope failure [15-18]. Back analysis serves as a crucial means to bridge the gap between laboratory test results and actual field conditions, enabling the accurate determination of material properties in failure cases, which are vital for efficient geotechnical engineering [19, 20]. It consists of direct and strain-based approaches requiring criteria for the acceptability of the simulation results.

The strain measurements approach to predict the failure of a geological material has been used in both underground and open pit applications [21]. Pit wall design experts [22, 23] have established strain limits to identify the onset of tension cracking, steady-state movement, and progressive slope failure. This strain-based approach to failure prediction shows promise as a tool for establishing strain thresholds that might be experienced before slope collapse based on rock mass quality [24].

Nonetheless, research on the strain-based approach in waste dump areas needs to be more comprehensive, and considering rain's impact on different slope stability issues is generally inadequate. Therefore, the main objective of this research is to evaluate the strain-based approach for predicting stability in waste dump areas. In addition, a back analysis approach using a coupled hydro-mechanical analysis evaluated in this study involves the soil's mechanical and hydraulic properties as the soil transits from unsaturated to saturated conditions, and the water table varies with time as rainfall continues.

2. RESEARCH SIGNIFICANCE

Previous studies on the strain-based approach focused solely on pit wall failure, neglecting waste dump areas. The influence of rain on slope stability issues and changes in pore water pressure during rain infiltration are poorly understood. This study evaluates the strain-based approach's suitability for predicting waste dump failure, utilizing a coupled analysis to simulate variations in pore water pressure and stress-strain relationships under realistic waste dump conditions. A thorough analysis using the back analysis method is crucial to comprehensively understand how rainfall characteristics and material properties affect slope stability. The findings can potentially enhance predictive capabilities and safety in mining waste dump operations.

3. MATERIALS AND METHODS

The research was conducted on the failure waste dump area of an open pit coal mine in Kutai Kartanegara Regency, East Kalimantan, Indonesia. The area was around 98 ha with a slope of 10°, constructed on sloping terrain with a dip direction of 02°N/180°E. The failure was circular, with major crack/failure measuring approximately 500 m in length and a maximum displacement of nearly 5 m. The study started with field observations, followed by collecting and analyzing historical rainfall, real-time monitoring data, and material properties data.

The waste dump samples were collected from eight boreholes at a 0 – 60 m depth from the surface (Fig. 1). A group of samples was taken to test grain size distribution (sieve analysis), hydrometer, and Atterberg limits. The number of samples considered the adequacy of the minimum sample requirements for each laboratory test parameter. All samples were undisturbed and placed in the thin wall tube (50 cm in length; 3 inches in diameter), which the structures, water contents, and chemical composition did not change. The samples were then transported to the Laboratory of Studio Mineral Batubara.

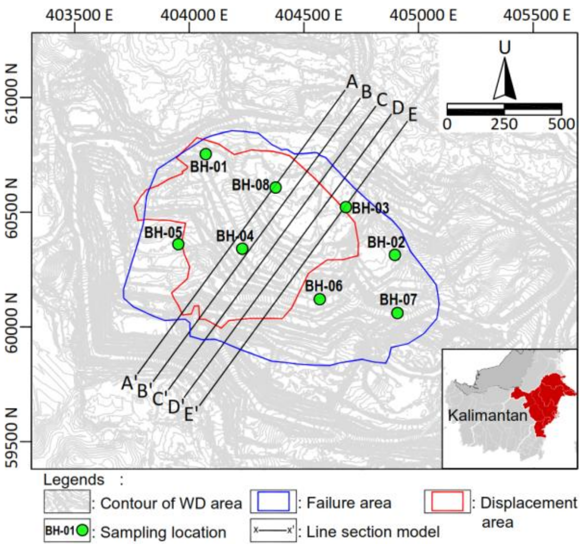

Fig. 1 Location of the study area

Considering the failure conditions, material properties, and rainfall data, this study's adopted methodology incorporated mechanical and hydraulic property to analyze the slope's response to variations in material saturation and groundwater level over time, particularly in the context of ongoing rainfall. A back analysis, coupled hydro-mechanical analysis (Fig. 2), was conducted to account for the influence of rainfall on failure events. Historical rainfall monitoring data provided a rainfall threshold, serving as representative input data for the transient stage. The back analysis of failure conditions was carried out at multiple stages within the analysis scenario to establish consistency between the developed model and the actual slope response observed at the research location before the failure. This alignment between the model and the observed slope behavior is a crucial validation parameter for the study.

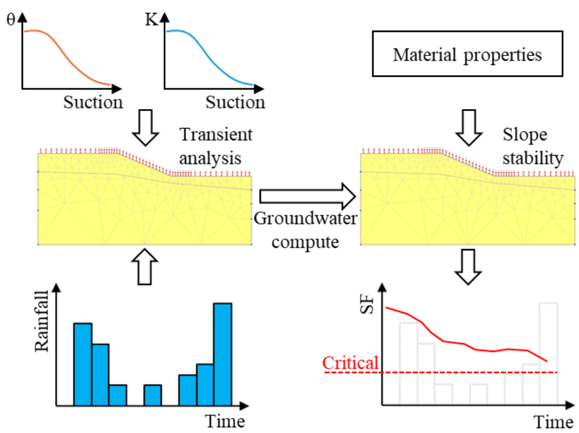

Fig. 2 Illustration of coupled analysis

Hydraulic parameters were simulated using the transient groundwater finite element analysis method. This method proved highly valuable in capturing the time-dependent behavior of intricate groundwater flows within the material. Including hydraulic aspects through this comprehensive analysis approach was crucial for thoroughly understanding both hydraulic and slope stability.

Slope stability analysis was conducted using the limit equilibrium and finite element methods by Slide2 and RS2 software. The mechanical properties were determined while the safety factor (SF) was less than 1 and suitability to the validation parameter through displacement and strain, as is shown in Fig. 3. The analysis started with the input of slope profile and boundary conditions, ensuring that the initial parameters and characteristics of the slope are adequately considered. Next, the flowchart emphasizes collecting input material properties, encompassing various physical, mechanical, and hydraulic parameters. These properties include soil composition, porosity, permeability, and shear strength, among others. By incorporating a comprehensive range of material properties, the analysis aims to capture the complex behavior of the slope with scientific rigor. Coupled analyses (scenarios 1 and 2) were integrated groundwater and stability analysis. This recognition of the interplay between groundwater and slope stability reflects a scientifically sound approach, as changes in water levels can significantly influence the stability of a slope. Considering groundwater's dynamic nature, the analysis acknowledges the time-dependent factors involved in slope stability assessment.

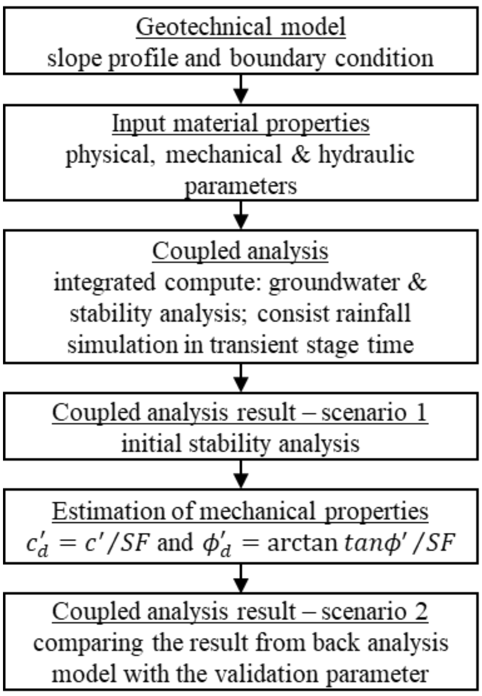

Fig. 3 Flow chart of this study

4. RESULTS AND DISCUSSION

4.1 Material Properties in the Study Area

4.1.1 Physical and index properties of waste dump samples

The physical and index properties were assessed to classify the materials and to analyze their unsaturated behavior. A series of physical properties, including dry unit weight, saturated unit weight, water content, and porosity, revealed values of 16.37 kN/m^3, 20.27 kN/m^3, 33.17%, and 43.52% for waste dump material, and 14.77 kN/m^3, 23.32 kN/m^3, 27.40%, and 41.27% for base waste dump material. These properties were determined in the laboratory, following the ASTM D7263-09 [25] and the ASTM D2216-19 [26] standard. Therefore, considering the saturated unit weight of 20.27 kN/m^3 for waste dump material and 23.32 kN/m^3 for base waste dump material, the materials are classified as soft to medium for the waste dump and stiff to hard for the base waste dump [16].

The index properties test included grain size distribution, specific gravity, and Atterberg limits on the waste dump samples were determined following the ASTM D422-63 [27], ASTM D854-14 [28], and ASTM D4318-17 [29] standard. The grain size distribution curve, derived from both sieve and hydrometer analyses, reveals the proportions of different particle sizes. This distribution correlates with the sizes of the pores or voids in the material. Atterberg limits were assessed to understand the material consistency, enabling the calculation of void ratio and water content as the material dries.

Table 1 presents the geotechnical index properties of the waste dump material. The specific gravity, which ranges from 2.32 to 2.68 (2.43), suggests that the materials contain a significant amount of organic matter and porous particles; however, the specific gravity of BH-07 indicates the presence of granular soils and inorganic clays [30]. This is supported by the consistency limits, which indicated some water-absorbing capacity in the materials.

The waste dump materials were classified according to ASTM D2487-06, Standard Practice for Classification of Soils for Engineering Purposes (USCS) [31]. The samples were found to contain a mixture of grain sizes, including gravel (>4.75 mm), sand (4.75 – 0.075 mm), silt (0.075 – 0.002 mm), and clay (<0.002 mm). The D_{10}, D_{30}, and D_{60} values and the Cc and Cu values shown in Table 1 indicate that the materials are generally well-graded. However, BH-05 was identified as poorly graded due to a Cc value of less than 1. The waste dump materials predominantly comprised 87.76% sand, 10.90% gravel, 0.81% silt, and 0.58% clay. The grain size distribution is consistent with the consistency limits data, showing that the high sand content results in a lower plasticity index.

Table 1. Summary of geotechnical index properties

Parameters	Borehole							
	BH-01	BH-02	BH-03	BH-04	BH-05	BH-06	BH-07	BH-08
Specific gravity	2.39	2.52	2.37	2.37	2.32	2.50	2.68	2.32
Liquid limit (%)	32.49	35.33	33.61	31.43	31.57	28.46	33.73	35.22
Plastic limit (%)	24.65	31.08	19.80	20.12	15.55	18.76	20.43	23.87
Plasticity index (%)	7.85	4.24	13.82	11.30	16.02	9.70	13.30	11.35
Gravel (%)	12.74	13.96	8.00	12.23	11.46	11.56	8.13	9.08
Sand (%)	85.76	85.16	91.00	86.40	86.71	86.83	90.87	89.32
Silt (%)	0.96	0.84	0.54	0.79	1.05	0.96	0.62	0.75
Clay (%)	0.54	0.39	0.46	0.58	0.78	0.64	0.38	0.85
D_{10} (mm)	0.22	0.27	0.18	0.19	0.23	0.21	0.17	0.15
D_{30} (mm)	0.83	0.93	0.63	0.75	0.70	0.75	0.61	0.54
D_{60} (mm)	2.43	2.56	1.65	2.35	1.84	2.30	1.71	1.69
Cc	1.26	1.24	1.32	1.32	0.98	1.19	1.29	1.14
Cu	11.21	9.97	9.31	12.74	7.78	11.02	10.09	11.34

4.1.2 Physical and mechanical properties

The study area is composed of two lithologies: the waste dump (WD) and the base waste dump (BWD), which serve as the overburden material or foundation of the waste dump area. Table 2 summarizes the physical and mechanical properties used in the back analysis model.

Table 2. Result of physical & mechanical properties

Parameters	Material	Value
Dry unit weight (kN/m^3)	WD	16.37
	BWD	14.77
Saturated unit weight (kN/m^3)	WD	20.27
	BWD	23.32
Water content (%)	WD	33.17
	BWD	27.40
Porosity (%)	WD	43.52
	BWD	41.27
Cohesion (kN/m^2)	WD	29.69
	BWD	110.19
Friction angle (°)	WD	24.61
	BWD	33.18
Modulus elasticity (MPa)	WD	1,101.43
	BWD	1.30E+04
Poisson’s ratio	WD	0.35
	BWD	0.33

The shear strength properties of in situ (undisturbed) samples include cohesion and friction angle. These properties were determined using a direct shear test apparatus in the laboratory, following the ASTM D3080-11 [32] standard. Samples collected from the field were prepared for testing, with at least three specimens carefully trimmed to maintain their lateral dimensions, avoiding disturbance or water content loss. A cylindrical cutting tool was used to precisely shape the specimens to fit snugly into the shear box, with a minimum diameter of 50 mm and thickness of 20 mm, or a diameter-to-thickness ratio of 2:1. Once placed in the shear box, the top and bottom surfaces of the specimens were carefully trimmed to be flat and parallel. The results of shear strength properties showed that the cohesion values for WD and BWD material are 29.69 kN/m^2 and 110.19 kN/m^2, corresponding to medium and very stiff consistency [33], while the friction angle values are 24.61° and 33.18°, reflecting very loose and medium dense relative density [33].

The stress-strain relationship is crucial for understanding material behavior under different conditions. It is characterized by the modulus of elasticity and Poisson's ratio parameters. These properties were determined in the laboratory, following the ASTM D2166-06 [34] standard. The modulus of elasticity values for WD and BWD material are 1,101.43 MPa and 1.30E+04 MPa. These values were not classified due to falling outside the range of soil type values. However, considering the Poisson's ratio values for WD and BWD material are 0.35 and 0.33, the soil type is classified as loose to dense sand and soft to medium clay [35].

4.1.3 Hydraulic properties

Unsaturated properties are crucial in influencing the rate of rainwater infiltration and variations in factor of safety over time. The hydraulic properties of unsaturated materials are governed by the soil-water characteristic curve (SWCC) and hydraulic conductivity function, which are necessary for analyzing seepage or water flow through material pores in relation to changes in matric suctions [10, 36]. The SWCC was derived using geotechnical index properties and measured grain size distribution data. The results of the SWCC estimation are shown in Fig. 4. The material exhibited an air entry value of 41.5 kPa for WD material and 11.5 kPa for BWD material. The high air entry value for the WD material is attributed to higher void space in this material.

The hydraulic conductivity function, which is non-linear concerning matric suction, requires various parameters derived from SWCC data and saturated permeability (K_{sat}) as inputs. The results of the hydraulic conductivity function estimation are shown in Fig. 5. The K_{sat} for WD material was found to be 7.76E-6 m/s, indicating fine-grained material, while the K_{sat} for BWD material was determined to be 1E-10 m/s, suggesting it is practically impermeable as the foundation of the waste dump.

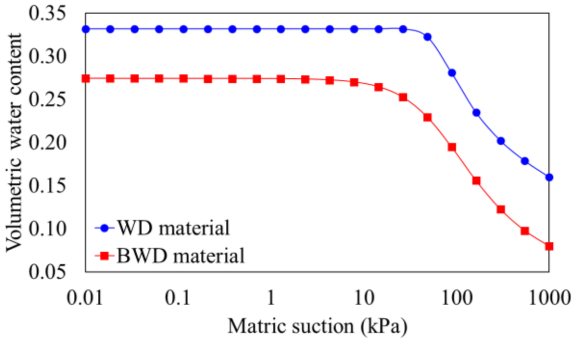

Fig. 4 Soil-water characteristic curve for waste dump samples

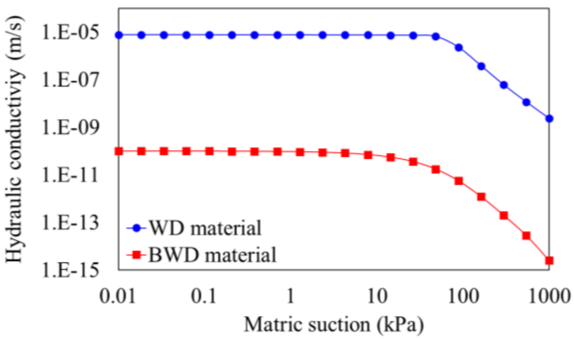

Fig. 5 Hydraulic conductivity function for waste dump samples

4.2 Scenario 1: Initial Stability Analysis

Back analysis in scenario 1 was conducted as the first step in the modeling process to assess whether the laboratory-tested material properties were suitable for representing the actual conditions during slope failure. Considering the variations in material properties, the analysis was performed on representative model sections A-A', B-B', C-C', D-D', and E-E' (Fig. 1) to obtain different safety factor values. Subsequently, corrections to the input material properties were made to adjust the actual slope conditions concerning waste dump failure and to represent the material strength during slope failure (whenever the safety factor (SF) was less than 1). The correction was applied using the shear strength reduction equation against the SF value, as demonstrated in Fig. 3, to represent the required material properties that would yield an SF ≤ 1.

4.2.1 Effect of rainfall on the safety factor

To investigate the influence of rainfall on slope safety factors, a coupled hydro-mechanical analysis was conducted to examine the response of the slope to changes between saturated and unsaturated material states, as well as variations in groundwater levels over time. The analysis incorporated the historical rainfall effects by combining mechanical and hydraulic parameters in transient finite element analysis stages. The back analysis results of the stability conditions in scenario 1 using the coupled hydro-mechanical analysis method, based on Fig. 6, indicate that the waste dump slope remains in a safe condition as it has a safety factor (SF) value greater than 1.00 and does not correspond to the actual slope failure condition observed on November 24th.

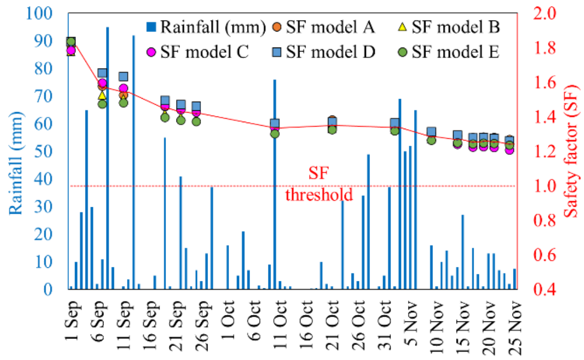

Fig. 6 Graph of safety factor for scenario 1

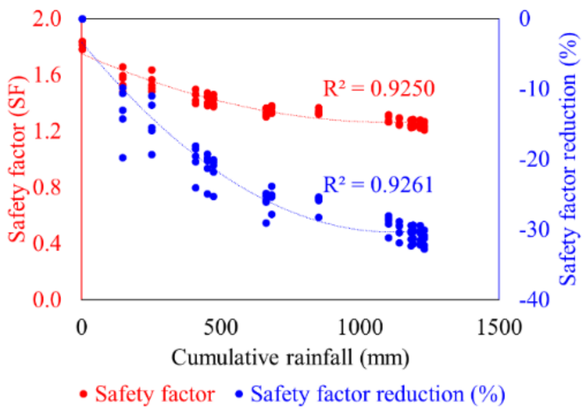

Fig. 7 Graph of SF & percent of SF reduction

Overall, the SF values gradually decrease as groundwater levels vary, leading to changes in pore water pressure within the slope material due to rainfall. Cumulative rainfall significantly decreases the average SF by 31.43% from the initial value of SF 1.811 to 1.242, as shown in Fig. 7.

4.2.2 Correction shear strength parameters

Previous studies have indicated that rainfall conditions decrease shear strength, thereby affecting the stability level and reducing the safety factor [11, 13, 14]. This indicates correcting the material properties representing the waste dump material conditions during slope failure. Back-calculated material properties were performed on shear strength parameters (cohesion and phi) [37], which have the most significant influence on the safety factor value [38]. The results of the properties correction to represent the waste dump material strength that would yield a safety factor ≤ 1 can be seen in Table 3.

Table 3. Recapitulation of corrected properties

Model	Cohesion (c_d' - kN/m^2)	Friction angle (phi_d' - °)
Model A	23.382	19.837
Model B	24.122	20.413
Model C	24.546	20.742
Model D	23.488	19.919
Model E	24.019	20.333

From the statistical analysis results using a Q-Q plot graph, as shown in Fig. 8, it is observed that the data distribution for the shear strength parameter follows a normal distribution. This is indicated by the data points aligning along the diagonal line, representing the ideal data condition following a normal distribution. Consequently, the cohesion (c) and friction angle (phi) parameters were corrected by 19.46% and 17.73% from their initial values of 29.691 kN/m² and 24.612° (Table 1), respectively, resulting in corrected values of 23.911 kN/m² and 20.249°, respectively.

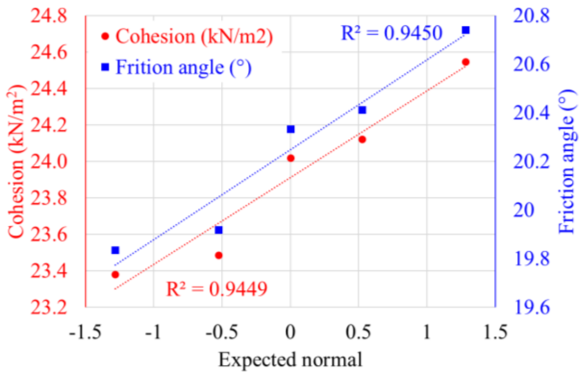

Fig. 8 Graph of normality test Q-Q plot

4.3 Scenario 2: Back Analysis Model Validation

Back analysis in scenario 2 serves as a validation step to assess the agreement between the created modeling and the actual response of the slope at the research site. The back analysis modeling was performed on representative sections B-B' and D-D' (Fig. 1), utilizing shear strength parameters obtained from statistical data processing based on material property corrections in scenario 1. Subsequently, the back analysis model will be validated against safety factor, horizontal displacement, strain, and the location of the sliding plane, which depict the actual conditions at the research site.

4.3.1 Validation of the safety factor

The slope failure in the waste dump area suggests that the safety factor values at the research site are ≤ 1, indicating a reduction in shear strength due to rainfall. Therefore, the correction in cohesion (c) and friction angle (phi) properties reflects this decrease in shear strength, leading to a safety factor of less than 1, which aligns with the actual waste dump failure conditions. Fig. 9 illustrates the gradual decrease in the safety factor values resulting from the historical rainfall effects, leading to an increase in pore water pressure, as shown in Fig. 10, which represents monitoring results at a depth of 15 m from the crown point of the sliding plane.

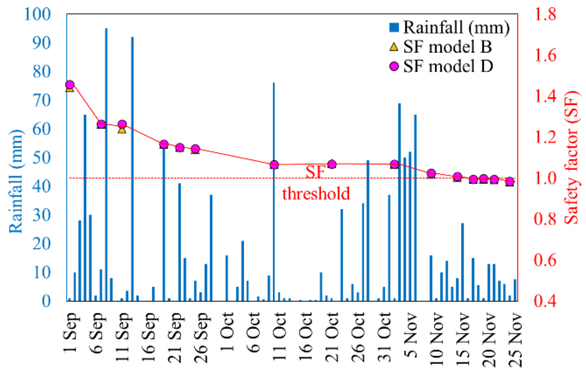

Fig. 9 Graph of safety factor for scenario 2

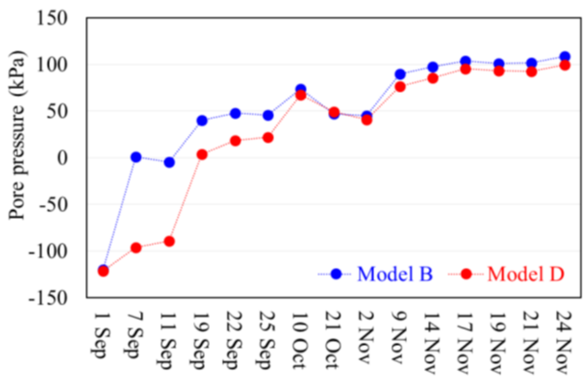

Fig. 10 Graph of pore pressure at a depth of 15 m

The distribution of pore water pressure changes in the slope can be accurately simulated using coupled hydro-mechanical analysis. The initial spike point, with a cumulative rainfall of 353.5 mm over 17 days, triggered the graph's transition from negative pore water pressure to positive values. Positive pore water pressure indicates the material is saturated, while negative values indicate unsaturated conditions.

The back analysis results using corrected shear strength input parameters indicate that the waste dump is unsafe, with an average safety factor (SF) value < 1, corresponding to the actual slope failure condition observed on November 24th. Furthermore, the average decrease in the safety factor reaches 32.07% from the initial value of 1.449 to 0.984 (Fig. 11). Therefore, the back analysis-derived material properties, based on the aspect of safety factor values, are acceptable as the actual material properties of the failed waste dump material. The regression equation for the correlation between the cumulative rainfall and safety factor is as follows:

$$SF = 3E\text{-}07x^2 - 7E\text{-}04x + 1.4086 \quad R^2 = 0.9722 \quad (1)$$

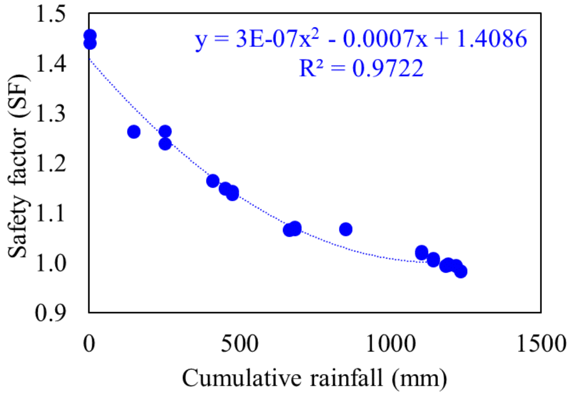

Fig. 11 Graph safety factor and cumulative rainfall

4.3.2 Validation of the horizontal displacement

This study obtained real-time horizontal displacement data from ground-based radar monitoring. Previous research has stated that the modulus elasticity (E) is the most influential parameter on deformation, and variations in the modulus elasticity (E) were considered to ensure that the back analysis model closely approximates the actual conditions or the occurrence of slope failure [38, 39]. Thus, in this study, the back analysis modeling utilized a modulus elasticity reduction (E_{red}) input parameter until a match was achieved between the model and the actual conditions.

Furthermore, the validation results of the back analysis model against the horizontal displacement parameter (m) are presented in the graph displayed in Fig. 12. Based on the results, it is observed that the model's displacement values and the actual readings from the ground-based radar during the same period yielded similar or close-to-actual results, with calculated differences ranging from approximately 0.66% to 5.28%. Additionally, the coefficient of determination (R^2) for Model B and Model D reached 0.9938 and 0.9891, respectively, indicating a good correlation between these parameters.

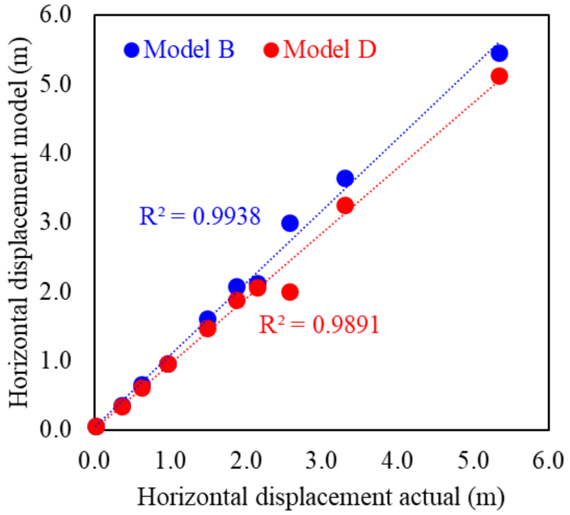

Fig. 12 Validation of horizontal displacement

The deformation at the research site consistently increased over time, indicating a decrease in the modulus elasticity (E) parameter. The reduction in the modulus elasticity (E) reached 99.37% from the initial value of 11,900 MPa to 74.53 MPa (Fig. 13), representing the actual condition of the failed waste dump. The regression equation for the correlation between the modulus elasticity and horizontal displacement model is as follows:

$$H_{displacement} = 251048x^{-0.871} \quad R^2 = 0.9897 \quad (2)$$

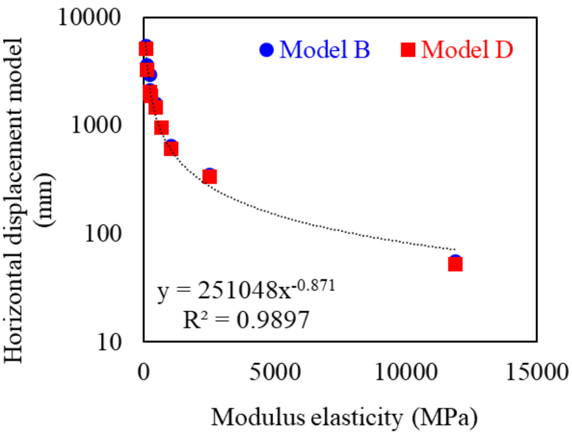

Fig. 13 Graph of horizontal displacement and modulus elasticity

4.3.3 Validation of the strain

The term 'strain' refers to the ability of a stressed material, in the presence of a stress field, to deform

[24]. Strain in a slope can be determined by comparing the deformation (Δx) with the height of the failure slope (H) and expressed as a percentage (%) [22, 24]. The deformation parameter utilized in this study is vertical displacement. The real-time movement data for this study consists of horizontal displacement obtained from ground-based radar monitoring. Consequently, the actual vertical displacement is derived from an empirical equation that correlates the horizontal displacement data from ground-based radar monitoring with the vertical displacement model. This is feasible due to the validation of the back analysis model, which indicates that the analysis results for the horizontal displacement parameter closely resemble the actual conditions (Fig. 12).

In order to accurately determine the vertical displacement in real-time based on 60 days of ground-based radar monitoring data with 15 daily displacement readings, an empirical equation is needed to adjust the overall horizontal displacement data. This equation will ensure that the vertical displacement has the same level of detail as the horizontal displacement, allowing for a comprehensive representation of the actual conditions. The analysis results are summarized in a graph (Fig. 14) to visually illustrate the correlation between the two parameters, indicating either a constant or linear increase. These findings align with previous research [39, 40]. The correlation between the two displacements is expressed by the following equation:

$$V_{displacement} = 0.7173H_{displacement} \quad R^2 = 0.9988 \quad (3)$$

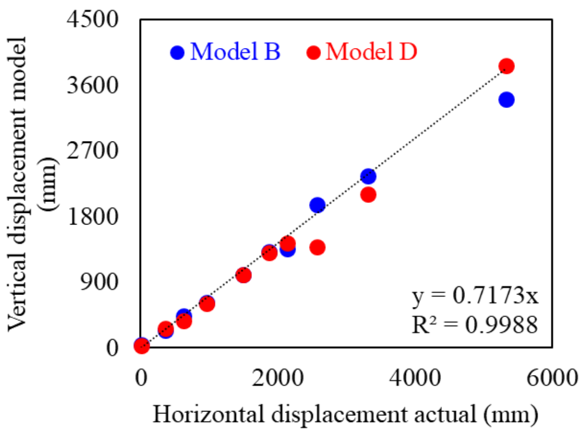

Fig. 14 Graph of horizontal and vertical displacement

Furthermore, the validation results of the back analysis model against the strain parameter are presented in Fig. 15. Based on the results, it is observed that the model's strain values and the actual values during the same period yield results that are not significantly different, with an average difference of around 31.44%, and a high coefficient of determination (R^2) for Model B and Model D reaches 0.9938 and 0.9891, respectively, indicating a good correlation between these parameters.

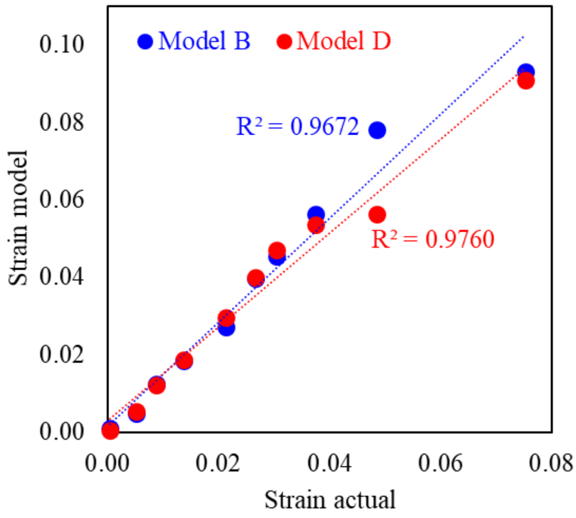

Fig. 15 Validation of strain values

Moreover, the actual strain values in this study can be developed as strain thresholds for predicting rock mass failure events in the waste dump area by developing a graph depicting the strain threshold - rock mass quality criteria. Previous studies [22, 23] explored potential correlations between rock mass rating (RMR) and strain thresholds by using a small dataset of twelve slope failures from various sources to test strain limits and compare them to rock mass quality. Due to the limited dataset size, slopes with different failure mechanisms and instability stages (e.g., initial cracking, steady state, and progressive) were analyzed together. One pit wall with rock mass failure collapsed with a strain of less than 0.1%, while the maximum strain recorded for a rock mass failure was about 3%.

Meanwhile, this study assumes a rock mass quality (RMR) for the waste dump material in the very poor to poor class (<21 - 40), taking into consideration the compressive strength values of the waste dump material being less than 1 MPa [16]. The assumption regarding rock mass quality classification is supported by previous studies, which consistently show that lower RMR values correspond to a lower rock mass modulus. This aligns with the findings of this study, where deformation at the research site increased over time, indicating a decrease in rock mass modulus, leading to lower RMR values. Classifying the rock mass as very poor to poor yields rock mass modulus values between 50 to 1000 MPa [41], which corresponds with the modulus values observed during the progressive failure of this study, ranging from 74.53 to 264.32 MPa. Generally, lower rock quality corresponded to higher potential strain at failure [22], and in this study, strain values consistently increased until failure occurred. The observed lower rock mass modulus and higher strain suggest that classifying the rock mass quality (RMR) as very poor to poor may be a reasonable basis for predicting rock mass failures. The variation in rock mass data is obtained using the random number generation method, assuming a uniform distribution. The waste dump conditions exhibiting progressive deformation from November 16th to November 24th represent the range of periods analyzed for strain values until the occurrence of the failure. The analysis results at the research site, as shown in Fig. 16, are consistent with previous research findings.

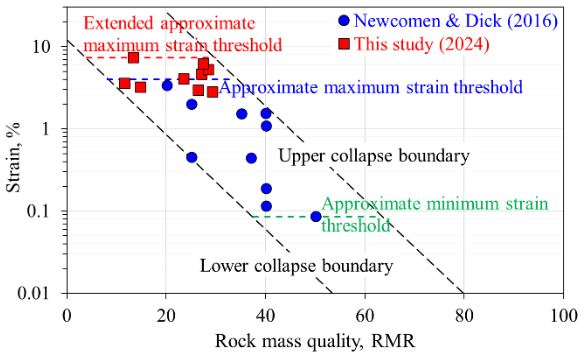

Fig. 16 Graph of strain threshold and rock mass quality for rock mass failure

It is observed that the strain values during the progressive slope period range from 2.79% to 7.36%. The development of the approximate maximum strain threshold graph can be performed due to the waste dump material being very weak, with a compressive strength value of less than 1 MPa (R0) and a rock mass quality classified as very poor to poor (<21 - 40). Consequently, higher strain values are expected during the collapse process. It is worth noting that the strain threshold graph in previous studies was conducted in the highwall slope area with rock mass qualities categorized as poor to fair.

Based on this study, the development of a strain threshold graph improves the ability to assess the stability performance of waste dumps by identifying key instability stages using empirical strain criteria. It can also be integrated into the trigger action response plan (TARP) for specific slope instabilities by setting a maximum slope displacement that would trigger further evaluations or more detailed stability assessments. However, it should be noted the developed strain threshold graph does not capture strain at depth or along the failure plane [23], and this failure prediction method requires caution, especially if the RMR changes over time due to deformation.

5. CONCLUSIONS

This paper presents a case study of back analysis of waste dump failure subject to rainfall. Coupled hydro-mechanical analyses were conducted, considering mechanical and hydraulic properties to capture the transition from unsaturated to saturated conditions as rainfall continues. The simulation results highlight the significant impact of historical rainfall on slope stability, with a 32.07% decrease in safety factor (SF) from 1.449 to 0.984, corresponding to the observed slope failure on November 24th. This decline in stability is attributed to changes in the waste dump materials' properties, with cohesion and friction angle values decreasing by 19.46% and 17.73%, respectively, compared to laboratory results. The corrected cohesion and friction angle values derived from the back analysis offer a more precise assessment of the waste dump's stability under actual field conditions. This enables better predictions of potential future movements or instability. The back analysis model aligns well with the observed slope behavior, validated by horizontal displacement and strain data, further indicating that a reduction in modulus elasticity correlates with increased displacement. A strain-based approach was also developed to predict rock mass failure, showing strain values ranging from 2.79% to 7.36%. Notably, the strain threshold for failure in the waste dump area exceeds that of previous studies in highwall areas, likely due to the lower rock quality, contributing to a higher strain potential at failure.

6. RECOMMENDATIONS

The findings of this study contribute to the existing literature on back analysis of waste dump failures by using coupled hydro-mechanical analyses to account for the mechanical and hydraulic properties of materials as they transition from unsaturated to saturated conditions during rainfall. This contrasts with the traditional safety factor evaluation in the waste dumps at open-pit coal mines, which did not consider the impact of water migration on materials during rainfall, leading to inaccurate results. Model validation showed that coupled hydro-mechanical analysis can accurately predict the deformation and failure of waste dumps under rainfall, making these results applicable to waste dump stability analysis and similar issues in other mining areas.

However, the study is limited by focusing on a single case study with specific material characteristics and hydrological conditions. In reality, rainfall and waste dump properties vary across different locations, and more comprehensive simulations with diverse material properties and rainfall conditions from various mining areas are needed for deeper analysis. Additionally, the results are limited to rainfall-induced waste dump failure, and further research is suggested to explore factors like dump material strength, geometry, time-dependent properties, and external loading conditions that may influence failure. These types of effects are subject to further investigation in future studies. In addition, incorporating slope displacement data with measurements of pore-water pressure and volumetric water content is recommended to reduce uncertainty in interpreting slope stability levels. The proposed approach offers valuable insights into the relationship between slope deformation, rainfall, and stability, but these factors were not addressed in this study and are open to further investigation.

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