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Slope Stability Geology and Soil Conditions during Road Construction along the Lupeta–Wimba–Izumbwe Road Intersections in Mbeya District, Tanzania

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ABSTRACT: In the realm of geotechnical engineering, maintaining slope stability is critical, especially in newly cut slopes during road construction. Consequently, the objective of this paper was to evaluate the Slope Stability Geology and Soil Conditions during Road Construction along the Lupeta–Wimba–Izumbwe Road Intersections in Mbeya District of Tanzania using appropriate standard procedures. Laboratory analysis determined shear strength parameters, with cohesion (c) ranging from 5 to 30 kN/ m², an angle of internal friction (Ø) between 20° and 35°, unit weight of soil (γ) varying from 16 to 20 kN/m³, and slope angles (α) between 25° and 45°. The study established a strong linear correlation between the angle of internal friction and the Dynamic Penetration Index (DPI), yielding a regression coefficient of 0.8, with the correlation equation Ø = 1.2515DPI + 0.3297. However, no reliable correlation was found between cohesion and DPI. The Finite Element Method (FEM) was employed to assess slope stability, revealing an overall factor of safety (FS) of 0.68, indicating slope instability. Acknowledging limitations related to pore water pressure and moisture content, the study introduces a quick methodology for slope stability monitoring using FEM, achieving early detection of slope failure.

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In developing countries like Tanzania, the construction of infrastructures such as roads, railways and bridges take up a significant role in economic development (Hearn *et al.*, 2021). In some cases, the construction of roads and railways are likely to cross landscapes where there are slopes which must be controlled to avoid failure. Slope failure results in Landslides which are considered one of the major natural hazards that cause enormous social and economic losses (Ray and Lazzari, 2020). To prevent such disasters include various methods of monitoring slopes in both natural and manmade slopes (Bromhead, 2019). This study assesses slope stability along the Lupeta – Wimba – Izumbwe road in Mbeya District, Tanzania. The research aims to develop a practical, cost-effective slope stability monitoring

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method using the Light Dynamic Probing Test (DPT). Dynamic probing test results are usually expressed in terms of Dynamic Penetration Index (DPI) in millimetres per blow (mm/blow). Apart from the advantages drawn from other existing methods of monitoring slope stability as described by other scholars (Zaki *et al.*, 2014), the adoption of monitoring the stability of slopes by using the Light Dynamic Probing Test addresses the limitations of current methods in terms of cost, availability, simplicity of data interpretation and identification.

Light Dynamic Probing Test provide effective solutions for detecting early activities related to landslide development and giving early warning to such failures (Bromhead, 2019). The factor of safety is a key element that is used to monitor the stability of the slope in the DPT method. This factor of safety can be estimated from shear strength parameters by several methods as described by (Pourkhosravania and Behzad, 2011). Combined with other exploration and investigation works, DPT provides a more complete insight into the geotechnical features of the investigated area (Lingwanda *et al*., 2017). Hence, the objective of this paper was to evaluate the Slope Stability Geology and Soil Conditions during Road Construction along the Lupeta–Wimba–Izumbwe Road Intersections in Mbeya District of Tanzania.

MATERIALS AND METHODS

Data collection involved specific slope sections along the Lupeta – Wimba – Izumbwe road, with a focus on "slope section A" for generating the correlation equations and "slope section B" for validation of the proposed correlations. Soil types were classified using the Unified Soil Classification System (USCS), employing sieve analysis and Atterberg tests. The Light Dynamic Probing Test (DPT) was performed during the rainy season, considering the impact of moisture content on Dynamic Penetration Index (DPI) values. Laboratory triaxial tests provided shear strength parameters for slope sections A and B. Correlation analyses were conducted, and a proposed correlation equation was developed between shear strength parameters and DPI.

Study Area: The study area is along the 10 km Lupeta – Wimba – Izumbwe road located in Mbeya District in Tanzania. The road is under construction to be upgraded to bitumen standard. At this road the roadside slopes have started to slide down due to heavy rainfall and other slope sections show signs of failure as seen in (Fig.1). In general, it is not possible to detect discontinuities within the agglomerates due to their textural properties (Kaya and Midilli, 2020). This gives a high chance of using the Light Dynamic Probing Test as a visible technique for monitoring the road slope stability from the beginning since the slope sections show no presence of agglomerates.

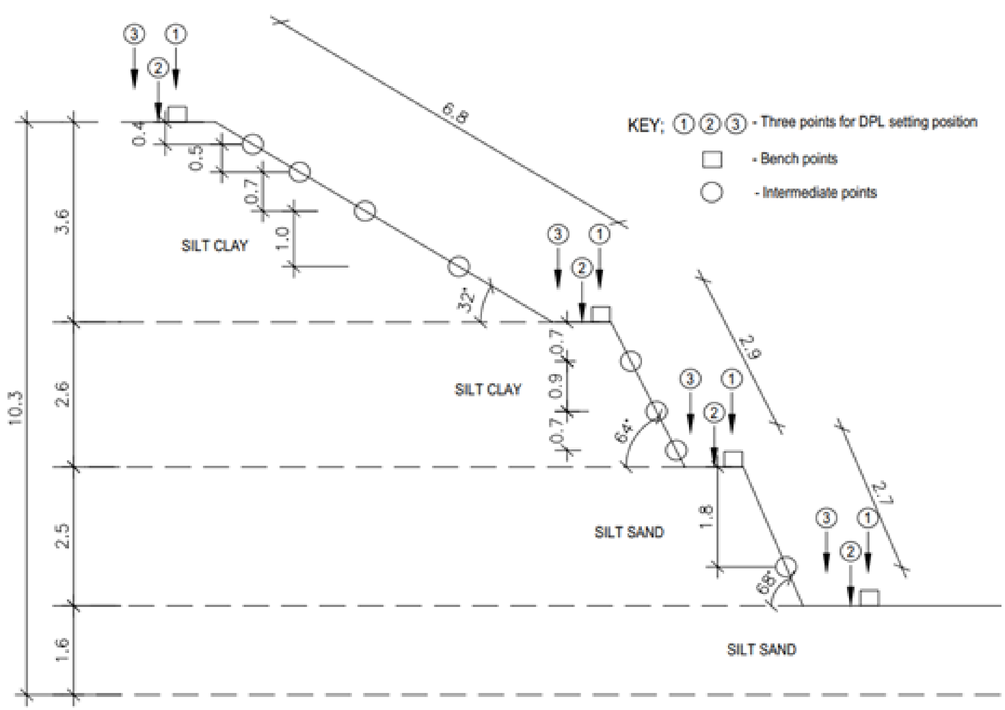


Fig. 1: Slope Section A along Lupeta – Wimba – Izumbwe road and Dimensional Layout

Field Soil Tests: In-situ field tests were performed by using a DPL device at the selected slope sections to obtain the DPI. Since the DPL device can be affected by the presence of stones and rocks in the soil, then average number of blows should be taken at each selected point (Perez *et al*., 2020). Field soil tests were conducted using light dynamic probing equipment which was performed at selected points of the slope sections A and B. Light Dynamic Probing has been described by ASTM D 6951-03, typically consisting of 10 kg hammer or less than drops over a height of 575 mm and drives a 60°cone tip with 20 mm base diameter vertically into the pavement or soil layer (Stumvoll *et al*., 2020).

The in-situ test was performed at four bench points to obtain the average number of blows at each bench point, as shown in (Fig.1). More than ten depth intervals between bench points were considered for data collection and soil samples were taken for laboratory test procedures to obtain a reasonable number of data pairs for correlation. Tools and equipment used were a tape measure, ladder, DPL and Excel sheet software for analysing DPI in mm per blow.

Laboratory Soil Tests: Laboratory tests were carried out using the Central Materials Laboratory (CML) manual guide on soil samples taken from the series of depth intervals at each selected point of the slope section where DPT was performed as shown in (Fig.1). The laboratory tests were performed per BS 1377 of 1990 and classified under the Unified Soil Classification System (USCS). Disturbed and undisturbed soil samples were collected from the field at depth intervals where the soil profile seems to change as depicted by the DPL test. Laboratory test procedures were then conducted for soil classification which involved both the Atterberg limit test and the Sieve analysis test. Then, a Triaxial shear test was conducted for the determination of shear strength parameters.

The triaxial test involved undisturbed soil samples which provide more accurate results and maintain their natural structure and moisture content (Komolvilas *et al*., 2021). The soil sample was taken undisturbed using triaxial cores in the laboratory since the cores for the triaxial test are smaller than the cores used for sampling at the field as shown in (Fig.2). Results of soil properties were tabulated in Table 1 to show a series angle of internal friction (∅), and cohesion of the soil (c) as well as classification of the soil at each depth of profile change.

Fig. 2: Field and Laboratory Soil Tests (a) Laboratory Triaxial Soil Test; (b) Field Dynamic Probing Test

Correlation equations: To estimate shear strength parameters from dynamic probing test results, correlation and empirical relationships were developed based on field and laboratory test procedures. The results were analysed to obtain a correlation between shear strength parameters by using conventional lab testing and DPI obtained from Dynamic Probing Test data. The correlation equation will be used to manipulate shear strength parameters from Dynamic Probing Test data.

In this study, the linear correlation equation was developed using Microsoft Excel software, the graphs were plotted, and the results were discussed. The linear correlation was done by considering shear strength parameters as the dependent variables and DPI as an independent variable. Moisture content affects the penetration resistance measured by dynamic probing test (Komolvilas *et al*., 2021) this effect was also observed in this study during data analysis and should carefully be considered in the interpretation of soil layers and properties. Data were analysed to identify patterns between moisture content and penetration resistance.

Validity of the Proposed Correlations: The first slope section A was used to develop a correlation equation between shear strength parameters and DPI while the second slope section B was used for validation. During the rainy season, field DPT data were collected and analysed for selected slope section B under the same procedures conducted during the performance of slope section A. Soil sample was taken from slope section B for laboratory test procedures and the comparison was made based on soil classification and natural moisture of slope section A.

According to Jarushi *et al*. (2020), the validity of the proposed correlation should be verified using test results on similar soils from different sites, which is why in this study consideration was made of soil type and moisture content range of 30% to 65% before proceeding with verification. Then, the laboratory shear strength parameters (c and Ø) for slope section B were determined by conducting a triaxial test under undrained conditions and the results were tabulated in Table 1. Statistical analysis was conducted to evaluate the significance of any differences observed between the results of shear strength parameters from the proposed correlation and the laboratory shear strength parameters obtained to test the validity of the proposed method.

Monitoring Method

Unlike traditional methods such as Limit Equilibrium Method (LEM), Finite Element Method (FEM) allows for detailed modelling of slope stability and varying boundary of soil conditions. The FEM considers time-dependent factors and employs advanced constitutive models to enhance the accuracy and realism of slope stability monitoring (Belytschko and Jacob, 2007). By using the method of slope failure criterion from the FEM, the factor of safety was determined along the sloping depth.

The input parameters were the angle of internal friction, cohesion, slope height, slope angle, unit weight of soil, normal soil stress, resisting force and driving force while, the output parameter is the factor of safety. These input and output parameters can be used in any of the FEM software. The results of a factor of safety from the generated correlation method using an Excel sheet software can then be estimated to show the stability of slope sections at Lupeta-Wimba-Izumbwe road.

RESULTS AND DISCUSSION

Geology and Soil Condition: Soil in slope section A consisted mainly of sand, with varying amounts of silts and clays mixed in while in slope section B consisted of mainly silt clay soil. From the sieve analysis test and Atterberg test results, the variations in soil types were categorized as silt sand (SM) and silt clay (SC) when classified by USCS. The DPT was performed during the rainy season due to the effect of moisture content in DPT data. This study shows that the presence of water in a soil's voids can have a significant impact on the engineering behaviour of soils. Based on the nature of soil along slope sections at the Lupeta – Wimba – Izumbwe road, this study gives a knowledge of the amount of water present, water content and the specific engineering behaviour that results from the water moisture. Dafalla *et al*. (2023) studied that, the increase in natural moisture content reduced the number of blows, but it might also weaken the soil structure, especially at the toe of the slope as it was also observed in this study. The laboratory analysis utilized an undisturbed soil sample to determine shear strength parameters accurately, maintaining the natural moisture content. Triaxial test was conducted under undrained consolidated (UC) conditions, assessing both soil cohesion and angle of internal friction. In undrained conditions, water drainage from the soil sample is prevented during shearing after saturation and consolidation (da Fonseca *et al*., 2023). To prevent shear failure, excess pore water pressure generated during the test was not allowed to dissipate under constant volume.

Table 1: The distribution of soil classifications and the properties of soil for slope section A

				Particle size distribution				Densities			Consistency			Triaxial shear	
s/n	Sample Depth (m)	Points for Slope A	Soil type	Clay 0.002 mm (%)	Silt .0002 to 0.063 mm (%)	Sand 0.063 to 2.0 mm (%)	Gravel 2.0 to 63 mm (%)	Bulk Density (mg/m³)	Dry density (mg/m³)	Natural water content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Friction Angle (Degree)	Cohesion (kN/m²)
1	1.50-1.95	1	SC	100	94-96	89-94	68-83	1.60	1.12	43.48	42	20	22	26	13
2	3.00-3.45	2	SC	100	100	100	83-99	1.63	1.15	42.35	41	20	21	24	27
3	6.50-6.88	3	SM	100	100	94-100	77-94	1.63	1.24	31.06	42	21	21	14	24
4	8.00-8.45	TOE	SM	100	100	96-100	85-96	1.61	0.98	63.74	46	22	24	13	6

Field Test Analysis: During the performance of DPT, the DPL was handled to ensure that the device stays upright even when the slope is steep as shown in (Fig.2). It was ensured that the device didn't tilt or lean due to the slope's angle, which could cause errors in the measurements (Ghorashi *et al*., 2020). The DPI was obtained by averaging the results of DPT data when three points were performed on each bench point, first at mid-depth, second at mid-depth +5 cm and third at mid-depth -5 cm. Throughout the performance of the DPT, careful measures were taken to maintain the upright position of the DPL device, even on steep slopes. Vigilance was exercised to prevent any tilting or leaning of the device caused by the slope angle, which could cause inaccuracies in the measurements.

Correlation Analysis: Slope section A was specifically selected for correlation generation, involving statistical analysis to establish a relationship between shear strength parameters and DPT data. The analysis focused on the average number of blows per 0.1 m across the entire depth of the slope, correlating with laboratory results of shear strength parameters at depth intervals according to the slope profile change. The findings were organized and input into an Excel sheet to establish the correlation. Graphical representations from the Excel sheet depicted linear correlations between the angle of internal friction and DPI values in slope section A. These correlations consistently displayed strong positive linear patterns, with an approximate regression coefficient of 0.8. The resulting proposed equation was determined as equation 1, where the angle of internal friction (y) depended on the number of blows (x).

In (Fig.3) graph (b) revealed no linear correlation between soil cohesion and DPI values in slope section A. The observed correlation consistently displayed weak negative patterns, characterized by regression coefficients of 0.061. The resulting equation, derived from this correlation, is expressed as equation 2, where cohesion (y) is dependent on the number of blows (x). Multiple regression analysis was further employed to enable predictions based on the relationship between shear strength parameters and the number of blows (DPI). The reliability assessment revealed that the linear relationship between the angle of internal friction and DPI values was reliable, while the linear relationship between cohesion and DPI values lacked reliability. This suggests the need for additional variables in the analysis to normalize the relationship between cohesion and DPI, considering how cohesion values can be influenced by varying moisture levels, as observed in this study. This finding suggests that DPI values can serve as a good indicator of the angle of internal friction in the soil, which is essential for assessing slope stability.

$$\emptyset = 1.2515DPI + 0.3297 \quad (1)$$
$$C = 0.0946DPI + 17.978 \quad (2)$$

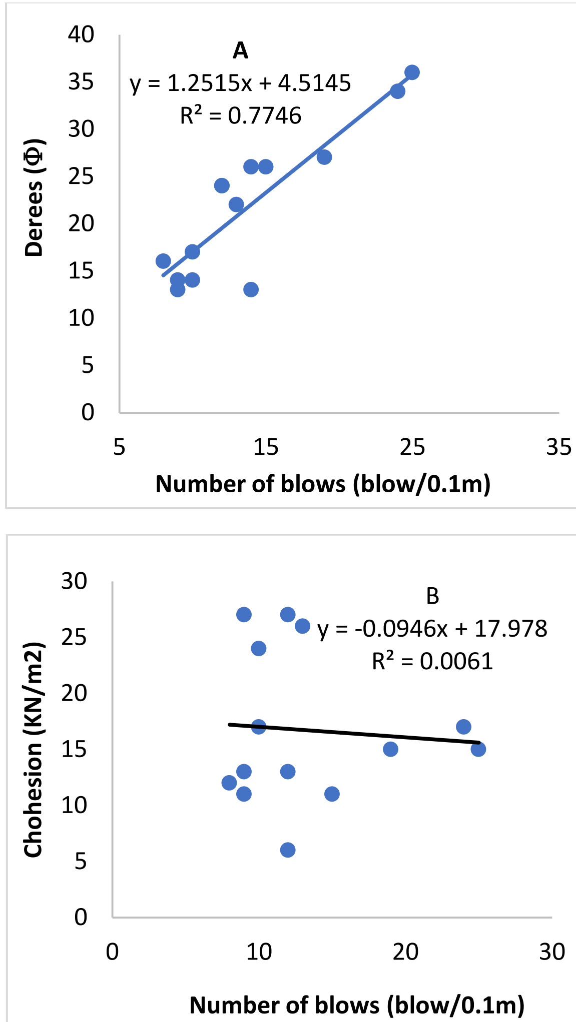


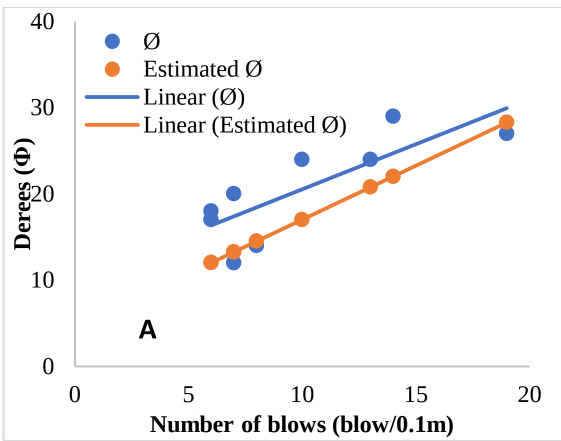
Fig. 3: Correlation between shear strength parameters and DPT data (a) Correlation between the angle of friction and DPI, (b) Correlation between cohesion and DPI

Compared with the correlation presented in (Mohammadi *et al*., 2007), the variation of nature and type of soil affects the correlation between shear strength parameters and DPI value. The proposed equation in (Mohammadi *et al*., 2007) for estimating the angle of internal friction from DPI for sandy soils containing 5% gravel, using the results obtained in their research. Their correlation was found to be exponential as shown in equation 3, unlike this research which was a linear correlation. Since the relationship between variables in the correlation was found to be proportional and additive, this study suggested linear correlations for simplicity of data interpretation. The inconsistency in the cohesion to DPI relationship in this research suggests that the cohesion correlation may not be specific to the conditions observed in slope sections as referred to equation 2 this was also presented by other researchers in (Sujit and Mandal, 2015).

Validation: Results from both laboratory tests and in-situ DPT were obtained for soil parameters in slope section B, and these findings are presented in Table 2. Utilizing an Excel sheet software, the shear strength parameter values for slope section B were estimated by applying the proposed correlation equations between shear strength parameters and DPI. The input for this estimation comprised DPI values obtained from the DPT conducted on slope section B, while the output was the shear strength parameters derived from the correlation equation. The tabulated results include values from laboratory testing and estimated values derived from the proposed correlation equations.

Table 2: Field and Laboratory Shear Strength Parameters for Slope Section B

Depth (m)	0.1	0.8	1.7	2.4	3.2	4	5.5	6.6	7.9
Average DPI (blow/0.1 m)	8	6	7	10	14	13	19	7	6
Laboratory, c (KN/m^2)	24	27	21	14	8	13	11	20	12
Laboratory, Ø (degrees)	14	18	20	24	29	24	27	12	17
Estimated, c (KN/m^2)	18.73	18.54	18.64	18.92	19.30	19.20	19.77	18.64	18.54
Estimated Ø (degrees)	14.53	12.02	13.28	17.03	22.04	20.78	28.29	13.28	12.02



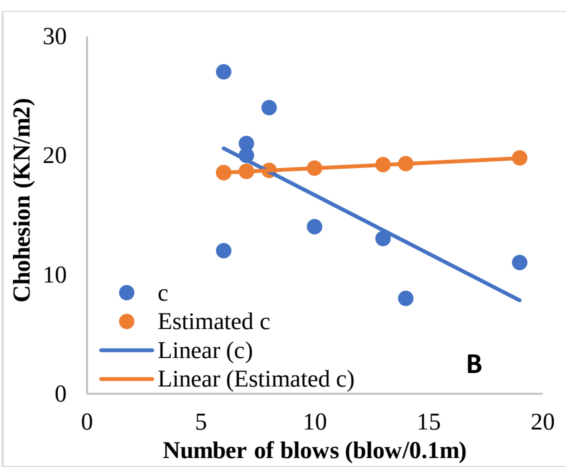


Fig. 4: Verification of the proposed correlation equations (a) Angle of internal friction Vs DPI; (b) Cohesion Vs DPI

The validity of the proposed correlation equations was examined using data from slope section B. In terms of the correlation between the angle of internal friction and DPI, both correlations exhibit similar linear patterns. However, for the correlation between cohesion and DPI, there is an opposite trend, suggesting that the proposed correlation equation may not be valid. The validation results offer support for the suitability of the proposed correlation equation, affirming the hypothesis of this research that there is a meaningful relationship between the light dynamic probing test data and angle of internal friction.

Conclusion: The correlation equation generated between shear strength parameters and Light Dynamic Probing Test (DPT) data revealed a quick methodology for monitoring slope stability using the Finite Element Method (FEM). A valid correlation equation was found between angle of internal friction and DPT data, thus eliminating the need for laboratory testing. Since no correlation was found between soil cohesion and DPI, further research is needed to refine the relationship between DPT data and soil cohesion. The analysis confirmed that the Lupeta-Wimba-Izumbwe road slopes are unstable, since a factor of safety was found less than 1. It is recommended that DPT be conducted when moisture content is between 30% and 65% for reliable results. A comprehensive geotechnical investigation is necessary to identify the specific causes of instability and implement appropriate slope stability measures.

Data Availability Statement: Data are available upon request from the corresponding author.

Declaration of Conflict of Interest: The authors declare no conflict of interest**.**

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