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The Prediction of Landslide Slip Surface Based on the Correlation Between Relative Density and Dynamic Cone Penetration Test

(Ramalan Satah Gelinciran Tanah Runtuh daripada Ketumpatan Relatif dan Ujian Kon Penembusan Dinamik)

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ABSTRACT

Relative density is one of the most important properties indicating the strength and state of compaction of the soil. The dynamic cone penetration test is considered one of the fastest field tests for evaluating the relative strength of soil layers, including density. In this study, an attempt is made to correlate the relative density of the landslide soil with the dynamic cone penetration results. The aim of this study was to delineate the boundary between moving and *in-situ* soil for the prediction of slip surfaces and finally to conceptualise the underlying mechanism behind the initiation of a landslide. The results of the penetration tests give an increasing index of 1.9 - 2.4 cm/blow, 2.8 - 3 cm/blow and 3.2 cm/blow for the upper, middle and lower parts (toe), respectively. Using the correlation equation, the calculated relative density in the field was found to agree well with the relative density measured in the laboratory with a standard deviation of ±1.5%. The relationship between the relative density and the penetration index shows an inverse relationship where the resistance of the soil to dynamic penetration increases as the relative density of the soil increases, thus decreasing the penetration index. This result can be used to accurately conceptualize the mechanism behind a landslide using a simple and rapid field device.

Keywords: Dynamic cone penetrometer; landslide; relative density; soil index properties

ABSTRAK

Ketumpatan relatif adalah salah satu sifat terpenting yang menunjukkan kekuatan dan keadaan pemadatan tanah. Ujian penembusan kon dinamik dianggap sebagai salah satu ujian lapangan terpantas untuk menilai kekuatan relatif lapisan tanah, termasuk ketumpatan. Dalam kajian ini, suatu percubaan dibuat untuk mengaitkan ketumpatan relatif tanah runtuhan tanah dengan keputusan penembusan kon dinamik. Matlamat kajian ini adalah untuk menentukan sempadan antara tanah bergerak dan tanah asal bagi penentuan satah gelinciran dan akhirnya untuk membangunkan mekanisme konsep di sebalik permulaan sesuatu tanah runtuh. Keputusan ujian penembusan menunjukkan peningkatan indeks sebanyak 1.9 - 2.4 cm/hentakan, 2.8 - 3 cm/hentakan dan 3.2 cm/hentakan, masing-masing untuk bahagian atas, tengah dan bawah. Menggunakan persamaan korelasi, ketumpatan relatif yang dihitung di lapangan didapati berkorelasi dengan baik dengan ketumpatan relatif yang diukur di makmal dengan sisihan piawai ±1.5%. Hubungan antara ketumpatan relatif dan indeks penembusan menunjukkan hubungan songsang dengan rintangan tanah terhadap penembusan dinamik meningkat apabila ketumpatan relatif tanah meningkat, lalu merendahkan indeks penembusan. Keputusan ini boleh digunakan dengan tepat untuk mengkonsepkan mekanisme di sebalik tanah runtuh dengan menggunakan alatan lapangan yang mudah dan pantas.

Kata kunci: Ketumpatan relatif; kon penembusan dinamik; sifat indeks tanah; tanah runtuh

INTRODUCTION

Landslides are one of the most common natural disasters that occur in Malaysia due to its climatic condition (intense rainfall in conjunction with the humid tropical climate), geological, morphology, lithology, hydrology and human activities (Cerri et al. 2017; Kazmi et al. 2016; Maturidi et al. 2021; Yao 2018). In general, landslide can be defined as slope failure in the form of soil slips, debris flow or rock falls that undergo different types of movements (Cruden 2003). The mechanism is generated by the movement of soil surfaces associated with gravitational attraction (Zulkafli, Abd Majid & Rainis 2023) that influenced by rainwater infiltration and its redistribution and soil characteristics (Ivanov et al. 2020). Along with the increasing urban population density, the development of highland or hilly areas is also increasing and this is putting pressure on the natural environment that can endanger human life and infrastructure (Diana et al. 2021).

Shallow landslides are one of the most damaging types that occur when the applied shear on the soil-bedrock interface exceeds the shear strength of the soil on a slope (Leonarduzzi, McArdell & Molnar 2021). The high frequency occurrences on hillsides often develop into a fast-moving debris flows (Oguz, Depina & Thakur 2022) as a result of increase in precipitation govern by the hydraulic parameters (Batumalai et al. 2023). Shallow landslides generally involve the slip page of the first few meters of soil or rock mixture, which can have implications for a wide area (Lee et al. 2013). The primary cause of rainfall-induced landslides is an increase in pore pressure in the soil, which decreased effective normal stress to a critical point. The larger soil bulk density that results from the rising moisture content of the soil additionally boosts the sliding force (Ran et al. 2018).

Universiti Kebangsaan Malaysia (UKM) has a long history of reporting landslide disasters, including most recently landslides that occurred in 2022 close to the Faculty of Education. Nineteen (19) slope areas in UKM were documented to have experienced landslides up until 1984 (Ibrahim 1984), including instances of minor inundation (Muhamad et al. 2019). It has been determined that 75 of the cut slopes, a type of man-made slope, on the UKM campus are geomorphologically failed slopes as a result of landslides (Ibrahim 1987), with the distribution of landslides occurring in vulnerability classes of medium, high, and extremely high (Muhamad et al. 2019).

The relative density of soil, evaluated as one of the most significant physical and engineering characteristics, is employed as an indicator of soil strength properties and as a control for compaction of the soil layers during construction (Alam, Hossain & Azad 2014). The value of relative density ranges from 0 to 100 percent with 100% being the densest and 0% being the loosest state of soil structure. The relative density of soil is an important factor to consider in geotechnical engineering, especially in construction projects that require stable ground (Maghvan, Imam & McCartney 2019). Soil with low relative density is more susceptible to settlement and instability as a result of higher void content, which can lead to soil deformation over time. Slope with loosest soil packaging has lower soil strength and is more prone to gravity-driven erosion and failure (Zhang et al. 2020). In the case of landslide area, relative density plays an important role in ensuring the strength of slope by reducing the permeability of soil and allowing more water to infiltrates.

The dynamic cone penetration test (DCP) is a portable *in-situ* penetration testing device that can assess ground soil strength profiles by calculating the penetration index (Du et al. 2016; Hong et al. 2019; McElvaney & Bundadidjatnika 1991). Due to its high mobility and simplicity, the DCP is appropriate for characterization of the slope at the slope's near-surface (Byun & Lee 2013). This test has been widely used to undertake quick, efficient, and safe evaluations of the soil layers' quality. It may also be used to describe a variety of soil characteristics in various ways (Mohammadi et al. 2008). Other soil characteristics, such as the California Bearing Ratio (CBR), dry unit weight, moisture content, shear strength, and unconfined compressive strength (UCS), were also connected to the data (Ayers, Thompson & Uzarski 1989; Kleyn 1975; Vordoagu, Boateng & Timol 2019; Wilches et al. 2018). However, the use of DCP for slip surface prediction is still scarce.

The aim of this study was therefore to correlate the relative density and the ground penetration index for a landslide area. The boundary between moving and *in-situ* soil for the prediction of slip surfaces is delineated and finally used to conceptualise the underlying mechanism behind the initiation of a landslide.

Materials and Methods

GEOLOGICAL SETTING OF STUDY AREA

The study area was a recent 100-meter-long shallow landslide reported in 2022 occurring at the Faculty of Education (FPEND), UKM within coordinates 101° 46' 31.52" E and 2° 55' 19.13" N (Figure 1). The area is underlained by the Keny Hill Formation, which consists of metasediment rock represented by sandstone, silt, and mudstone in Carbonaceous age (Samsudin, Hamzah & Ramli 2007), which then underwent low grade regional metamorphism processes (Hussin et al. 2017) and altered to quartzite, schist, and phyllite (Jaafar, Yusof & Yahaya 2011; Muhamad et al. 2013). According to Ibrahim (1984), Bangi is made up of three dominant geological features: alluvium, granite, and metasediment in the UKM campus area, which is made up of fine-grained phyllite metasedimentary rocks containing quartz, crolite, and muscovite minerals. The surface outcrop is actively weathering from grade III to VI, with the residual soil comprising of sandy loam, sandy silt, and silty sand (Muhamad et al. 2013; Prashanthan 2019).

The slope area can be divided into five zones ranging in degree of weathering from IV grade (highly weathered) to VI grade (residual soil). Weathering grades IV to VI indicate that the weathering in this area and its surroundings is very active. The phyllite rocks have distinct foliation and the formation of numerous quartz veins. The outcrop also has a high concentration of quartz grains, owing to the extensive influence of weathering and erosion processes on the slope. The presence of this many large quartz grains, as well as weathering and erosion factors affecting the region's rocks, demonstrates the weakness of phyllite rocks and their low resistance to weathering and erosion processes, eventually cause them to erode easily.

Preceding the landslide event, the 45° slope experienced a high infiltration of water due to massive pipe burst on top of the hill side. The sudden increase in water volume causes a decrease in the friction force between the coarse-grained soil and cohesion bond between fine-grained soil. The presence of soil with a predominance of gravels and poorly graded sand increases the capacity for infiltration and hydraulic conductivity of the ground, which in turn, causing extreme precipitation prior to failure. The existence of rills and gully as a common erosional feature in phyllitic soil with dispersive behavior, could also promote the occurrence of shallow landslides in this area (Shah, Nazer & Harris 2022).

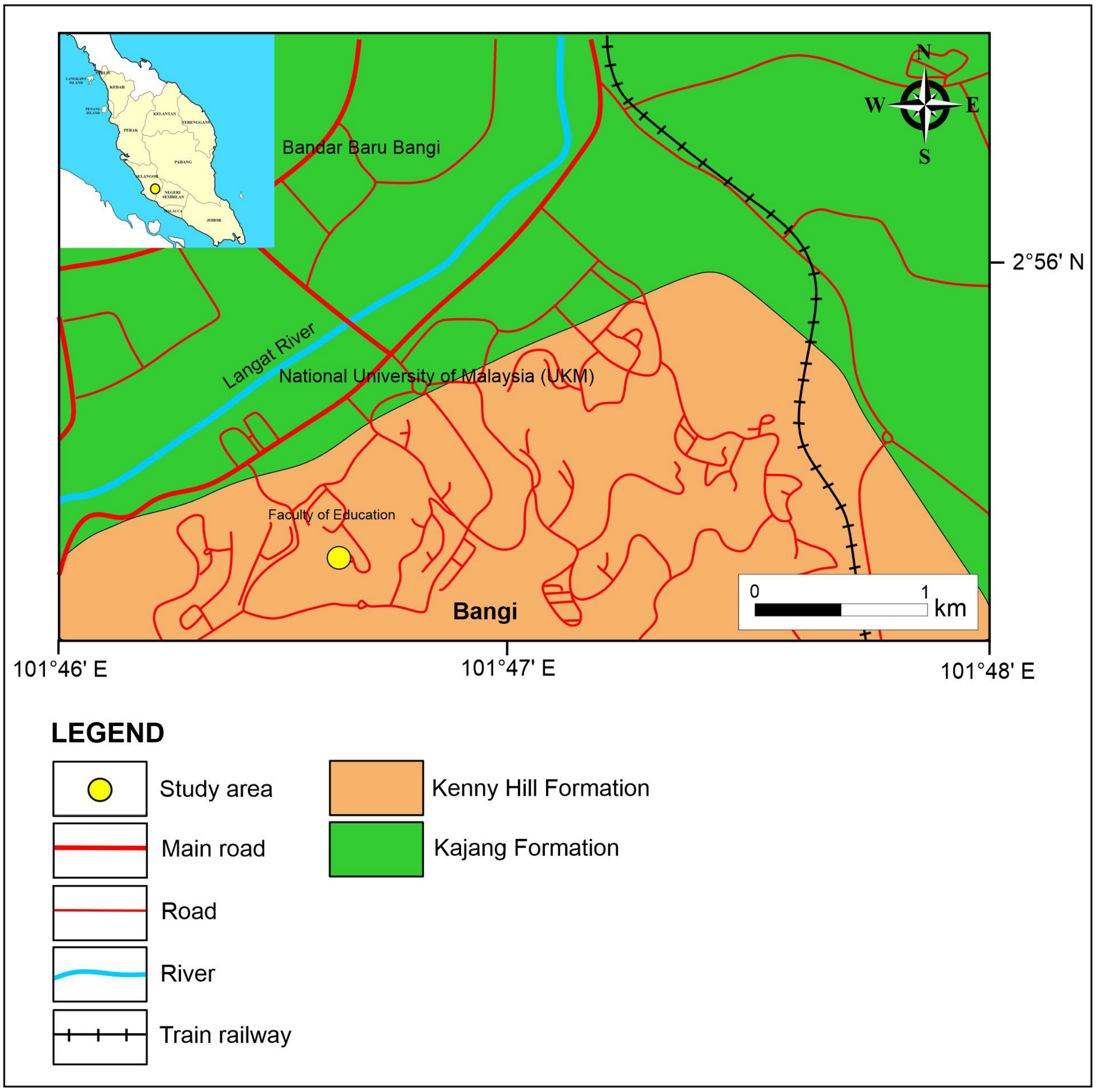

FIGURE 1. a) Geological map and locality of soil sampling in the landslide area

MATERIALS & PHYSICAL PROPERTIES OF SOIL

In this study, 6 disturbed soil samples weighing 5 kg each were collected from 3 different zones along a 100 m stretch of the landslide area using the hand auger technique to test relative density. The depth at which the samples were taken was set at 10 cm from the ground surface to minimise the impact of the atmosphere on the soil. The soil was tested exclusively for the accumulation zone representing the landslide deposits. Each samples were designated as T_a and T_b (top zone) M_a and M_b (middle zone) and T_{0a} and T_{0b} (toe zone). Each samples were then divided into 2 groups; the first group was used to determine the relative density of each sample, and the second group was used in laboratory tests to identify the physical properties of soil. The soil physical properties include mositure content (BS1377: 1990, Test (A)), particle size distrubtion - sieve and hydrometer (ASTM D6913/D6913M–17/ASTM D7928–17), specific gravity (G_s) (ASTM D854–14: Method A) and soil consistency – liquid and plastic limit (ASTM D4318–17e1).

FIELD DENSITY AND RELATIVE DENSITY MEASUREMENT

The field density (γ_d) in this study was determined using the core cutter method. It was a rapid method conducted in the field. This method depends on the use of a cylinder core cutter of known volume that has been placed in the soil for which the field density is to be determined. For the sake of simplicity, the soil structure was considered homogenous along vertical soil profile. Before starting the test, the diameter (D) and height (H) of the cylindrical core are measured, and its volume (V) is determined by using equation (1). Using the volume of the core (V) and the weight of the sample (Ws), the field density (γ_d) is calculated using equation (2). This test is repeated at the 6 points from which the samples were taken, and the field density value is used to measure the relative density of soil.

$$V = \pi\left(\frac{D}{2}\right)^2 H \tag{1}$$

$$\gamma_d = \frac{W_s}{V} \tag{2}$$

The relative density, D_r of soil is determined from Equation (3). The determination of the maximum index density (γ_{max}) and minimum index density (γ_{min}) is following the ASTM 4253 (2006) and ASTM 4254 (2006) standards but with minor modifications. The vibrational force by a vibrating table is replaced with a mechanical shaker and the steel-cylindrical mold used in this test was taken from the proctor test apparatus.

$$D_r = \frac{\gamma_{max}}{\gamma_d}\left(\frac{\gamma_d - \gamma_{min}}{\gamma_{max} - \gamma_{min}}\right) \tag{3}$$

where H is the Height of the mold; D is the Diameter of the mold; V is the Volume of the mold; γ_{max} is the Maximum index density; γ_{min} is the Minimum index density; γ_d is the Field Density from Equation 2.

DETERMINATION OF SOIL PENETRATION STRENGH AND PENETRATION INDEX (PI)

Soil penetration index (PI) is measured using a DCP test in accordance to ASTM D6951-09R15. The principle of DCP test is based on dropping a hammer of mass (M) through a height of fall (H) on an anvil to drive a probe cone. The DCP consists of two shafts, upper and lower. The upper shaft includes a hammer with a known mass (M) of 8 kg (17.6 lb) and a height (H) through which the hammer falls equal to 10 650 mm (65 cm) connected to the rod. The lower shaft is a rod consisting of an anvil at the top and a cone with an apex angle of 60 degrees and a diameter of 22.5 mm at the bottom, separated by 1000 mm (100 cm) (Figure 2). The measured penetration force is defined as the number of blows required to penetrate a certain distance within the layers. The distance caused by each blow is also measured (cm/blow), to determine PI value.

STATISCAL DATA ANALYSIS

Through the results obtained from the relative density test in the laboratory and the results obtained through the DCP measurements in the field, the correlation between the relative density and the penetration index is studied through statistical analysis using the Excel software.

RESULTS AND DISCUSSION

PHYSICAL PROPERTIES, DENSITY AND DCP RESULTS

Table 1 shows the results of the physical properties of the soil of the study area. The values of the natural moisture content of the soil samples that were collected from the landslide area range from 15% to 34%. The highest value in the moisture content of the six samples is 33.39%, and it represents the first point, which is located in the top zone of the failure slope. The G_s values of the soil samples range 2.60 to 2.63. All samples were classified as coarse textured soil (gravel and sand) with a percentage value exceeding 90%. The samples showed sand gravel size particle content ranging from 42%-61%, sand content ranging from 38%-54%, silt content ranging from 0.03%-0.18% and 0.27%-2.38%. The soil in the study area is classified as are poorly graded gravel with sand (GP), well graded sand with gravel (SW), and poorly graded sand with gravel (SP) based on the uniformity coefficient (Cu) and coefficient of gradation (Cc) on the curvature graph (Figure 2(a)). The soil PL value in the study area ranged from 16.56%-36.73%, while the LL ranged from 28%-59%. Based on Figure 2(b), the PI value is in the range of 5.48%-25.38%, where the soil sample is described as low to high plasticity cohesive soil. An LL value below 50% indicates the nature of the soil is less plastic with limited water particle holding capacity.

Field density values for the six points ranged from 1.20 g/cm^3 to 1.53 g/cm^3, with the lowest value measured in the top zone of the landslide and the highest value in the toe zone (Table 1). The relative density of the field samples representing the study area ranged from 33% to 75%, with an average of 49%. Based on the relative density results, the soil in most samples was classified as loose to moderately compacted, indicating a colluvium boundary layer transported from the area of origin. The results from DCP showed that the greatest penetration depth was reached in the toe zone of the failed slope. This was considered the weakest zone compared to the top and middle zones. These results are also consistent with the relative density results in relation to the strength of the layers in each zone. The upper zone has the highest value of relative density and resistance to penetration, and these values decrease towards the lower zone in the area of the lower slope (Table 1).

CORRELATION, VERIFICATION AND VALIDATION OF RESULTS

The relative density was calculated in the laboratory for each sample and the results are shown in Table 2. From the results and the statistical analysis, it can be seen that the relationship between the relative density, Dr and the penetration index (PI) is inversely proportional (Figure 3(a)). The relative density of the soil is highest when the soil is cohesive, so the penetration index decreases with it and the resistance of the soil to penetration increases. The linear equation linking relative density and penetration index was derived from Equations (4) by statistical analysis with an R2 value of 0.9882.

$$D_r = -30.76\ PI + 133.83 \tag{4}$$

TABLE 1. The results of physical properties of soil

Parameter			Soil sample					
T_a T_b			M_a	M_b	T_{0a}	T_{0b}		
Moisture content (%)			33.39	26.88	21.22	23.20	19.70	15.57
Specific Gravity, Gs			2.62	2.62	2.60	2.60	2.62	2.63
PSD	Coarse size	Gravel (%)	57.98	46.69	59.19	50.95	42.76	61.04
		Sand (%)	41.18	53.00	40.34	48.34	54.43	38.27
	Fine size	Silt (%)	0.11	0.03	0.06	0.10	0.40	0.18
		Clay (%)	0.71	0.27	0.39	0.60	2.38	0.49
Plastic limit, PL (%)			23.03	36.73	27.61	32.38	23.51	16.56
Liquid limit, LL (%)			47	59	53	47	29	28
Plasticity index (PI)			23.96	22.26	25.38	14.61	5.48	11.43
Field density (g/cm^3)			1.20	1.33	1.25	1.35	1.40	1.53
Laboratory relative density (%)			74.04	60.70	49.97	43.03	34.38	33.34

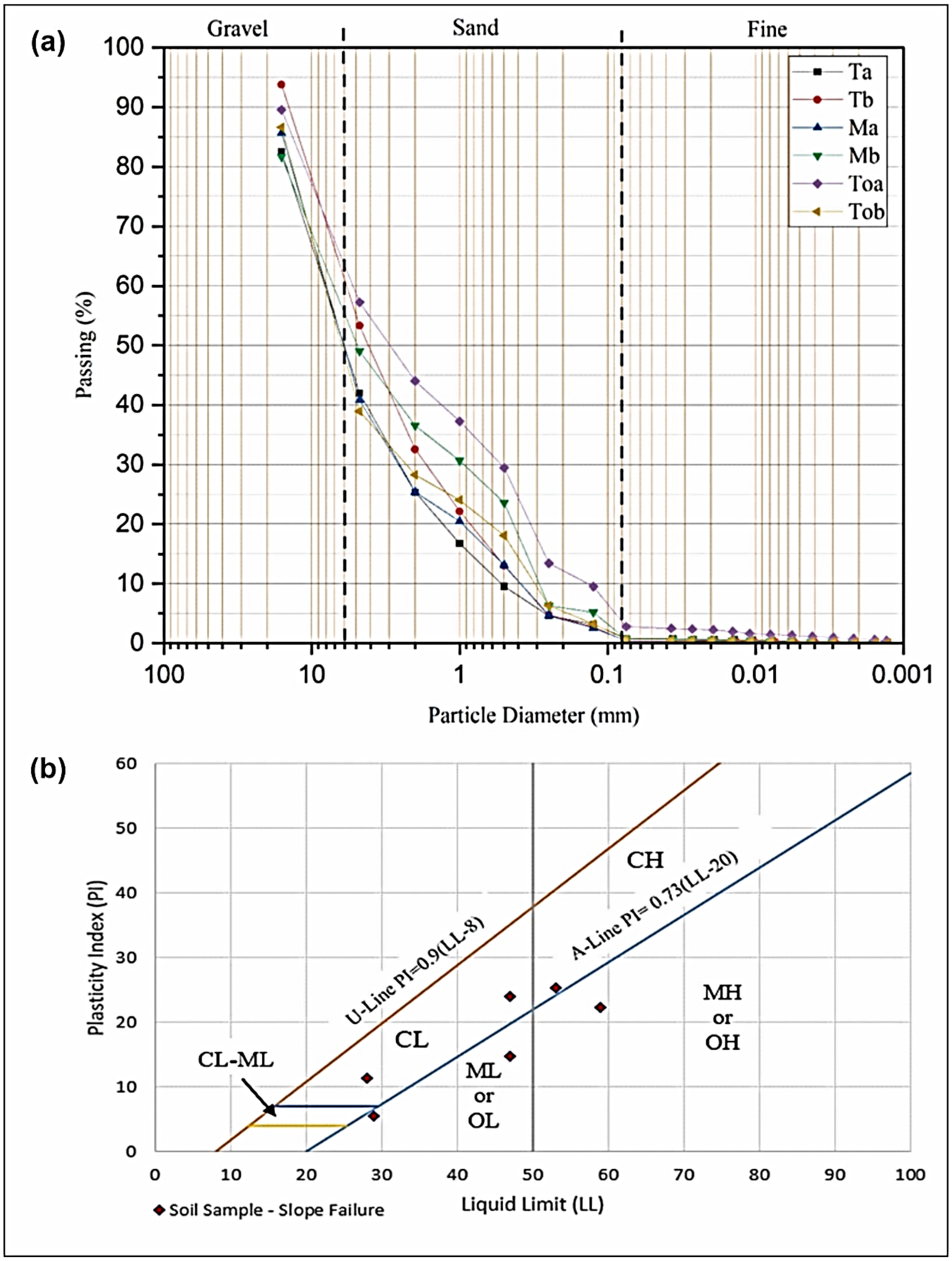

FIGURE 2. The figure illustrated (a) Particle size distribution curve; (b) Plasticity chart to determine the PI value of the soil samples

After establishing the relationship between penetration index and relative density calculated in the laboratory and deriving the linear equation linking the two properties, the correlation was verified against the DCP field results. Using the correlation equation in Equation (4), the relative density of the penetration index was calculated. The relative density results calculated from the DCP field test are shown in Table 2 and the comparison of the laboratory and field relative density results is shown in Figure 3(b). From the results, it was found that the standard deviation of the relative strength correlation was ±1.5%. This was considered satisfactory as it shows a higher correlation accuracy between two different datasets.

According to studies from Alam, Hossain and Azad (2014), MacRobert, Bernstein and Nchabeleng (2019), and Mohammedi et al. (2008), the relationship that combines the relative intensity and the penetration index showed an inverse relationship. As the relative density increases with the increase in soil resistance to penetration, the penetration index of DCP in the layers decreases, and this was confirmed by the results of this study. Figure 3(c) compares the correlation results between findings in this study and relative density values obtained from Alam, Hossain and Azad (2014). The correlations were in good agreement and show a satisfactory linear curve projection between 2 different soil types. Alam, Hossain and Azad (2014) conducted the DCP and relative density tests on a pure sand sample, while this study used soil samples from a landslide area along the colluvium depositional zone. The structural difference between coarse-grained and mixed-grained soils are likely to results in different relative density values. Densely-packed soils typically having higher relative density values due to lower void ratio. The loose soil configuration in landslide soil shows higher void ratio similar to coarse soil. However, the presence of fine-grained soil as a result of *in-situ* weathering significantly decreased the void ratio of soil, resulting in a lower relative density value.

A higher penetration index indicates a lower relative density of the soil and thus a weaker soil structure. Ideally, a typical landslide profile according to Varnes (1978) shows a thinner soil deposit in the upper region (head to main body), a thicker soil deposit in the middle (main body) and a thinner soil deposit in the lower region (foot to foot). However, the vertical correlation with the relative density of the study area indicates a planar slip surface with thicker deposits at the bottom, which is atypical for residual soil failure (Figure 4). The landslide is believed to have moved at a higher velocity following the bursting of water pipes running parallel to the slope. The sudden downpour of water could likely cause the soil at the surface to move downward with the flowing water, washing away wetting front material, including large trees and gravelly rocks. This could be an indication of premature shallow slip surface of a residual metamorphic soil slope occurring within a short period of time.

TABLE 2. Comparison of relative density results obtained from laboratory and field

Sample point	Penetration index (cm/blow)	Relative density (laboratory results) (Dr%)	Relative density (field results) (Dr%)
T_a	1.9	74.04	75.386
T_b	2.4	60.7	60.006
M_a	2.8	49.97	47.702
M_b	3	43.03	41.55
T_{0a}	3.2	34.38	35.398
T_{ob}	3.2	33.34	35.398
Avg.	2.75	49.245	49.24

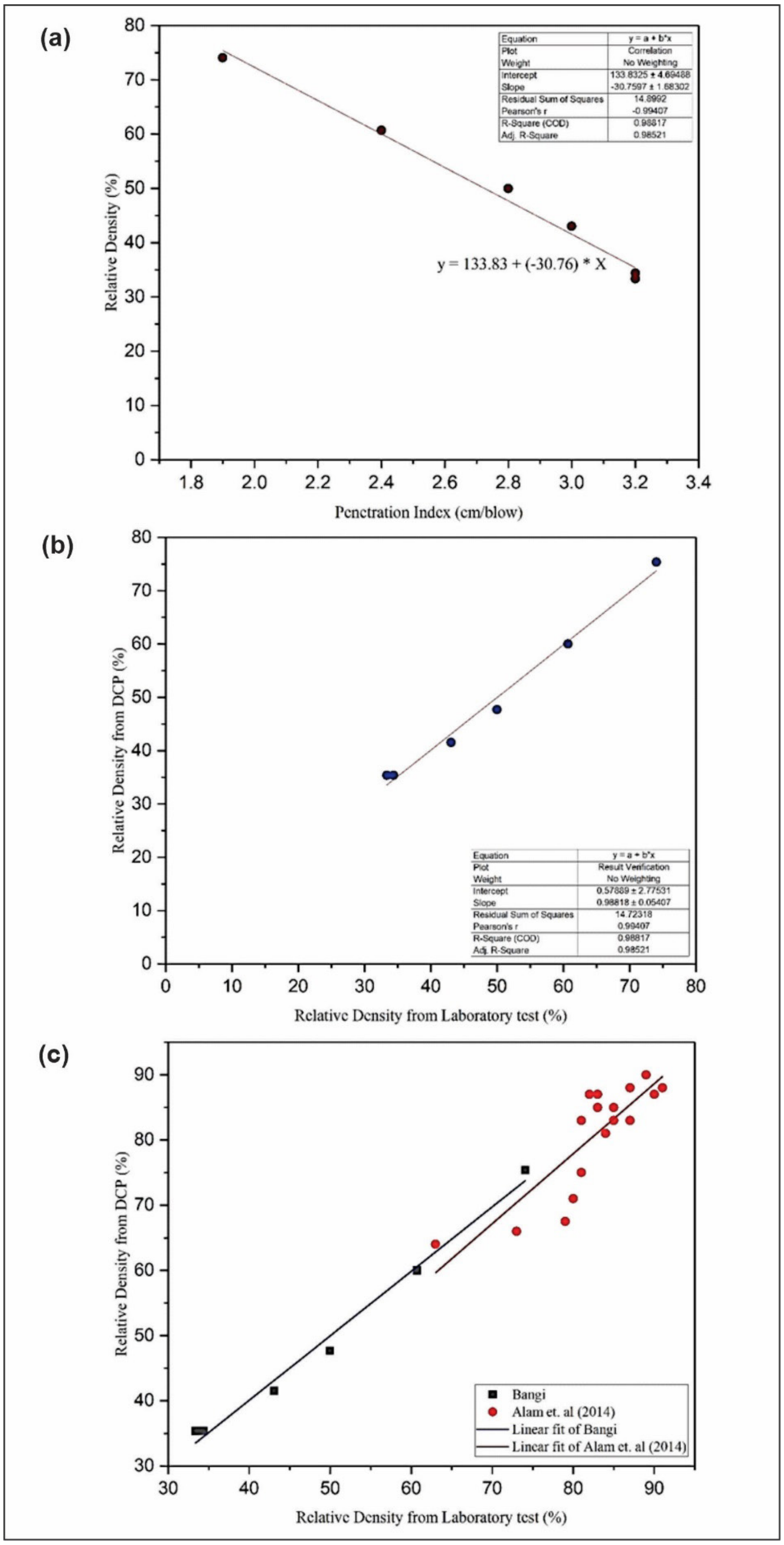

FIGURE 3. Figure shows (a) Correlation between the relative density and penetration index of soil samples (b) Comparison of relative density results obtained from laboratory and field (c) Comparison between relative density results of this study and the results from Alam, Hossain and Azad (2014) study

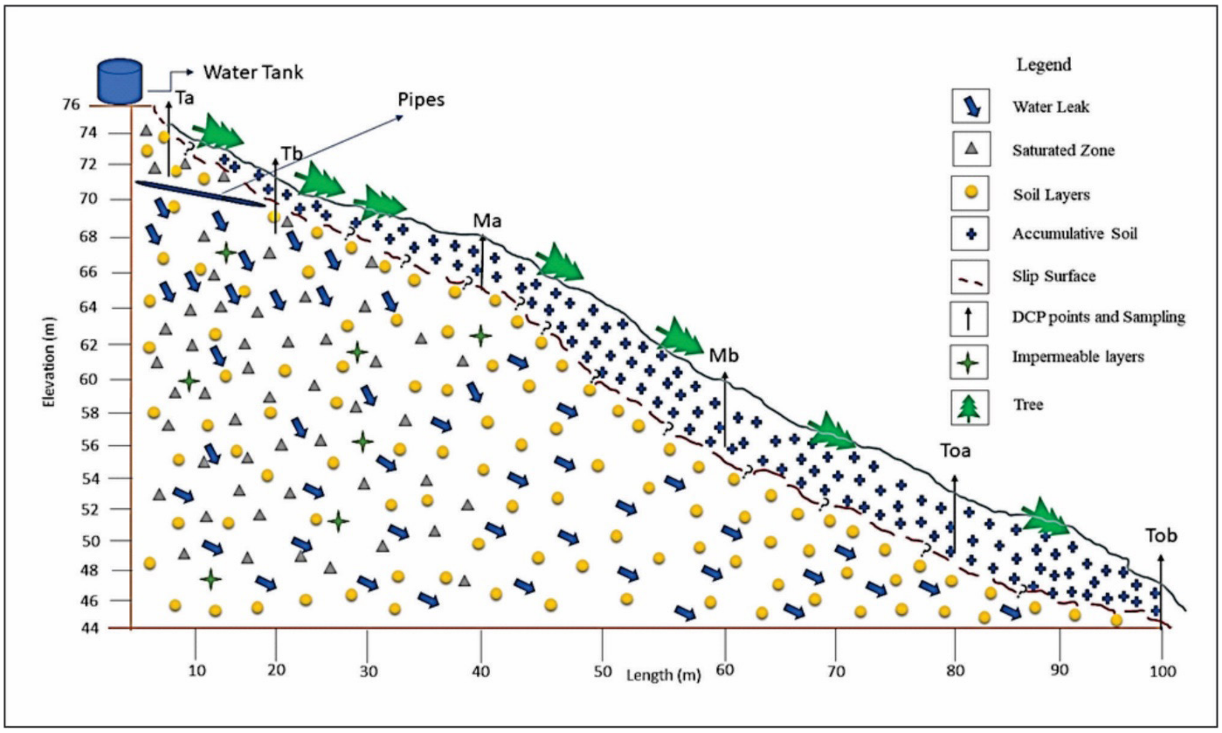

FIGURE 4. Cross-sectional view of the shallow landslide in UKM

CONCLUSION

Relative density can be considered as one of the promising soil index properties for landslide studies, providing insight into the natural configurational state of the soil structure. The DCP penetration test, on the other hand, provides a rapid testing method and can be associated with many indices for classification purposes. Overall, the attempt made in this study to correlate relative density with DCP test results provides good conceptual insight into the probability of a shallow landslide. The correlation equation shows higher accuracy between field and laboratory data and can therefore be extended to different landslide types for a more complex subsurface investigation. However, this method has been shown to be applicable only to failed material deposits and is limited to penetration indices of 4.5 and below. The inclusion of relative density for stable soils results in a much smoother regression curve, allowing a broader penetration index for a wider range of relative density. It is therefore recommended that the DCP and the relative density test be extended to different parts of the landslide to develop a more comprehensive model.

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