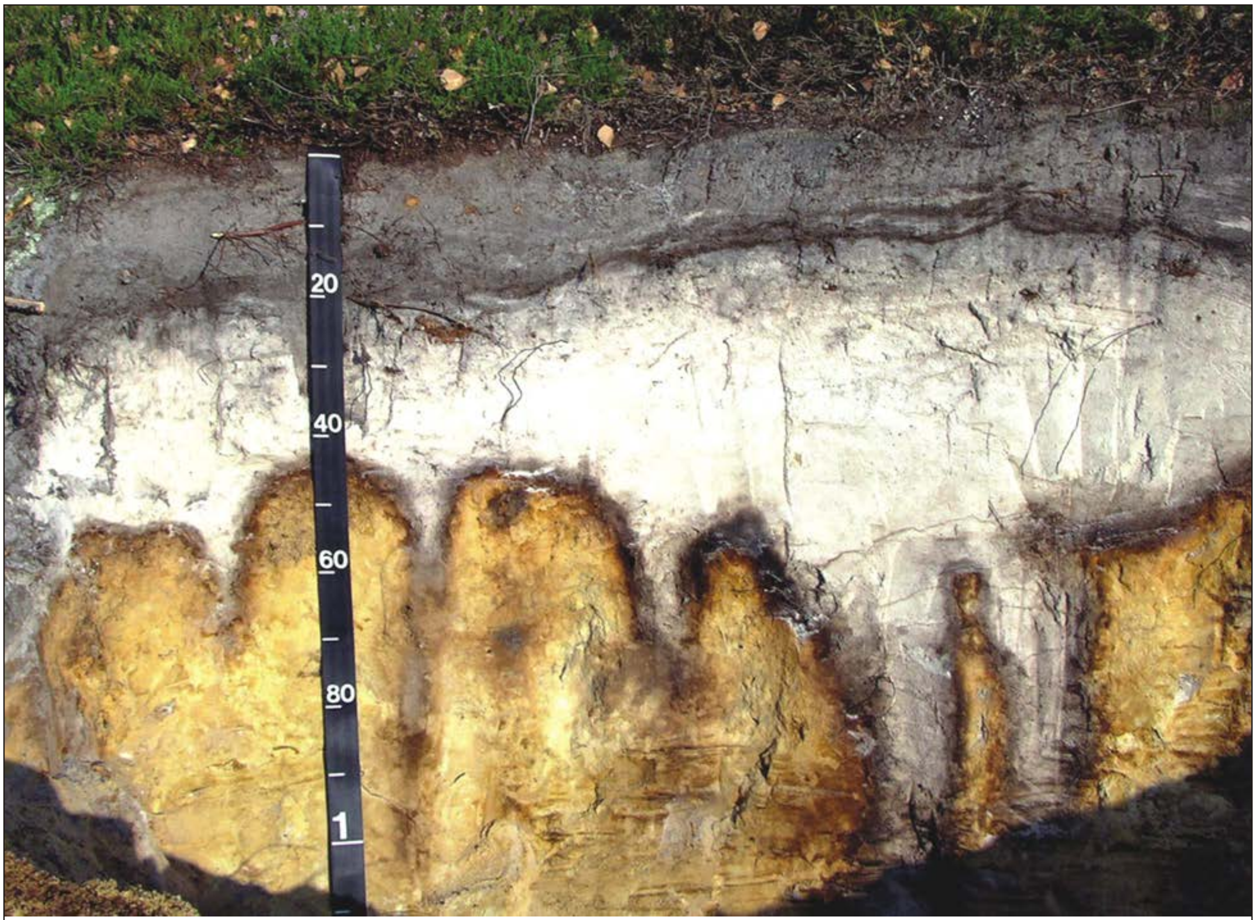

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Research Article
Effects of Variable Angular Velocities and Soil Moisture Contents on Undrained Shear Strength in a Sandy Loam Soil (Eutric Leptosol)

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Abstract

The study discusses the empirical derivation of undrained shear strength S_{und} from vane tests and compared this to those derived from predictions under the influence of both angular velocity (ω) and Soil Moisture Content (SMC) percentage. The study conducted on partially and fully saturated samples of sandy loam soil (Eutric leptosol) evaluated the effects of three different angular velocities and Soil Moisture Contents (SMCs) on the S_{und}, using a pocket vane tester. The angular velocities used in this study were 7.2, 3.6 and 1.8° sec^{-1}, which corresponded to rotation rates of 5, 10 and 20 sec per 0.1 kg cm^{-2}, respectively. The results showed that S_{und} positively correlated with time to failure (t_f) irrespective of change in the angular velocity and negatively correlated with both (ω) and SMC, which both were best described using a power function: $S_{und} = \Lambda\theta^{-\beta}$. The S_{und} was constant at any given SMC regardless of variations in angular velocity however, the S_{und} decreased with increase in SMC suggesting that S_{und} was largely controlled by SMC and less by w. Decoupling the torque into the cylindrical and horizontal shear components showed that the shear resistance generated by the cylindrical or vertical torque (T_v) was more or less constant around 0.1 kg cm^{-2} till failure, whereas the shear resistance generated by the horizontal torque (T_h) was variable at about 0.3 kg cm^{-2}. On average, the T_h was three times the T_v, while the measured S_{und} was overestimated by about 40% higher than the predicted S_{und}.

Key words: Angular velocity, Eutric leptosol, soil moisture content, undrained shear strength, vane tester

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Although, much research over the decades has focused on the undrained behavior of saturated clays, studies on the behavior of partly or unsaturated sands is now gaining interest especially within the context of liquefaction and stability of soil supporting geotechnical structures. Liquefaction phenomenon can be described as the reduction of the shear strength due to pore pressure buildup during mechanical loading. In essence, it is a reduction in soil shear strength as influenced by the degree of saturation during loading sequence (Tsukamoto *et al*., 2002). The undrained shear strength of desaturated sand can be influenced by the presence of air bubbles that alleviate pore pressure buildup during loading (He *et al*., 2014) of partially saturated sands during triaxial tests (Kamata *et al*., 2009) and of saturated sands during triaxial tests (Tsukamoto *et al*., 2004). In partly saturated agricultural soils, the shear strength can affect the performance of cultivation of implements, root growth, least limiting water range and traffic ability. In very simple terms, soil strength is the maximum shear stress it can sustain prior to failure, where a shear slip occurs along a surface. If the shear velocity is slow enough to allow the pore water in the soil to drain, this is the drained shear strength. Conversely, if the shear velocity is too fast not to allow the pore water to drain, this is the undrained shear strength. In this case, there is no change in the soil water content.

Owing to its simplicity and versatility, the vane tester has been used in the field and laboratory in the estimation of the undrained shear strength of mostly saturated clay soils. However, the interpretation of results derived from such tests has been influenced by such factors like: Non-standard shear rate, anisotrophy or rod friction effects (Schlue *et al*., 2007; Schlue *et al*., 2010; Wiesel, 1973; Lerouiel and Marques, 1996; Donald *et al*., 1977), delayed time between vane insertion and rotation (Terzaghi *et al*., 1996), disturbance due to vane insertion (Chandler, 1988), initially disturbed soil (Kulhawy *et al*., 1983) and stress path (Mayne *et al*., 2009).

The main objective of this study was to study the effects on the undrained shear strength of sandy loam soil under different soil moisture contents and shear angular velocities.

The pocket shear vane tester is a simple instrument that was used to obtain an approximate measurement of the undrained shear strength (S_{und}) of a semi-cohesive sandy loam soil. The measurement is obtained by applying a force (torque) needed to rotate the blades inserted into the soil to cause the failure of cylinder portion of undrained cohesive soil. Much of the shear resistance of the soil is distributed along the cylindrical surface as well as at both top and bottom ends, where the vane blades cuts the soil. The undrained shear strength is directly read out on the graduated scale in kilogram per centimeter square.

For purposes of simplicity, we assume that the components of the stress tensors of an infinitely small cube at any point where the vane blades cuts the soil are on three mutually perpendicular planes: x, y and z are equal in magnitude, with the corresponding shear forces in the opposite directions. Clearly, two things happen on the shear resistance t_f upon application of torque at failure: (1) Either if the angular displacement, ω is less than 90° ($\omega<90°$) and (2) Or if this were greater than 90° ($\omega>90°$). Based on $S_{und} = \pm f(\sigma_n)$, as in case 1, the sign of S_{und} will be positive, while this will be negative as in case 2.

Shear resistance τ_f during torque application takes place along the cylindrical surface and at bottom end of the 8-blade vane. Considering that the vane blades were the equivalent to the entire diameter (D mm) of the vane foot except for a circular separation distance of the steel rod with diameter (d mm), the shear resistance generated by the torque along the cylindrical or vertical surfaces can be expressed as:

$$T_v(\omega) = (D\text{-}d)\, 2\pi r h \tau_f \tag{1}$$

where, $T_v(\omega)$ is torque kg cm^{-2} along cylindrical or vertical surface with angular rotation (ω), (D-d) is equivalent of blade length (Fig. 1a-c), h is height of vane blade (mm). Similarly, assuming that only the bottom end of vane tester offers shear resistance by the torque applied once fully inserted into soil, this on a single vane blade may be expressed as:

$$T_h(\omega) = \int_0^{D-d} (2\pi dr d\tau_f) r \tag{2}$$

where, $0 \le r \le D\text{-}d$.

$$T_h(\omega) = 2\pi\tau_f \int_0^{D-d} r^2 dr = 2\pi\tau_f \left[\frac{r^3}{3}\right]_0^{D-d} = 2\pi\tau_f \times \frac{(D-d)^3}{3} \tag{3}$$

$$T_h(\omega) = (D-d)^2 h\tau_f + 2\pi\tau_f \frac{(D-d)^2}{3} \tag{4}$$

$$T_h(\omega) = (D-d)\left\{h - \frac{D-d}{3}\right\}\tau_f \tag{5}$$

$$T_h(\omega) = \tau_f (D-d)\left\{H - \frac{D-d}{3}\right\} \tag{6}$$

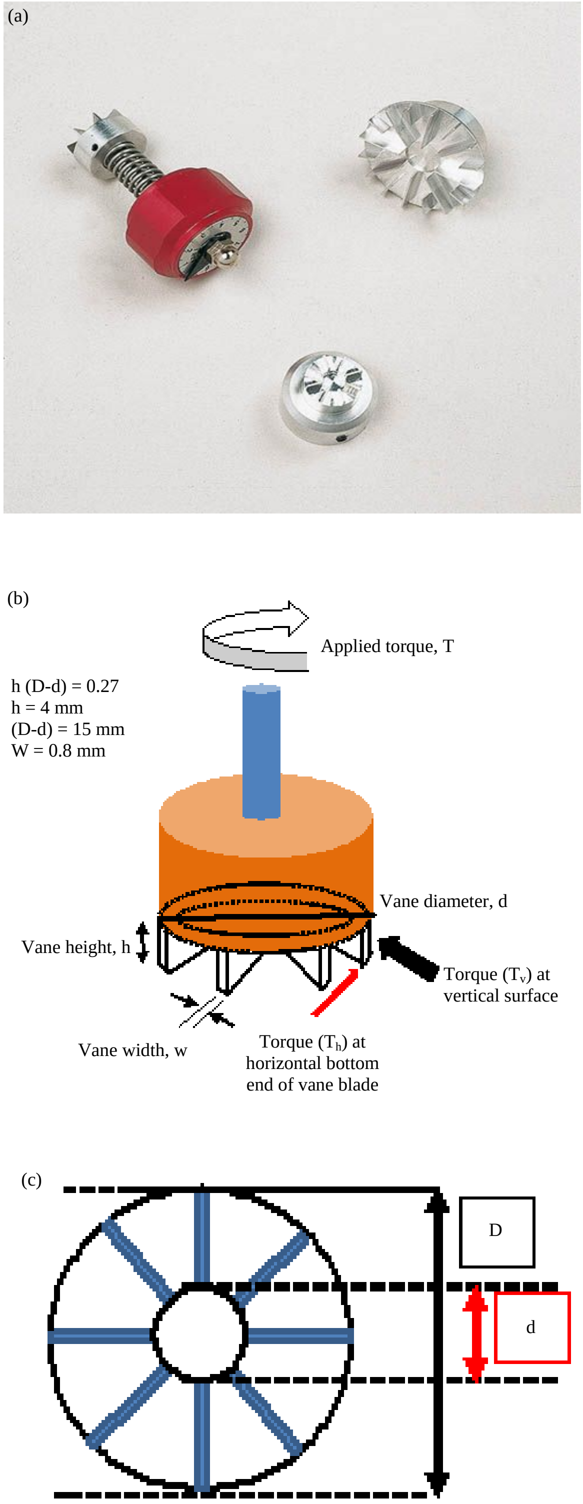

Fig. 1(a-c): (a) Pocket vane tester with adapters, (b) Technical characteristics of pocket vane tester and (c) Differences in diameters of, D: Diameter of pedestal containing the vane blades, d: Diameter of steel rod and D-d: Length of vane blades

Dividing both sides of Eq. 6 with:

$$(D-d)\left(H-\frac{D-d}{3}\right)$$

gives the estimated value of τ_f and this is the equivalent of S_{und}. If h/D-d≥0.5, then this negligible, otherwise it must be multiplied by a factor-4 if h/D-d≥0.5.

Equation 1 implies that the τ_f especially for cylindrical surface will be uniform, whereas, at the bottom end of vane blade this varies progressively failing toward the center (Eq. 6) (De Alencar *et al*., 1988; Silvestri and Aubertin, 1988).

MATERIALS AND METHODS

Study site: The study was carried out over a 4 month period as from May-August, 2015 at the Research and Demonstration Farm, Department of Agricultural Sciences, College of Natural Resources and Environmental Studies (CNRES), University of Juba, South Sudan. The study area lies within the Green Belt Agrological Zone of South Sudan and is located between latitude 4°50"28 and longitude 31°35"24 with average annual rainfall of 650 mm mostly during the months of April-October. The climate of the area is tropical wet and dry climate with average temperatures ranging between 27°C during the rainy seasons to about 35°C during dry season. The soil type is a sandy loam soil, Eutric leptosol with less associated Eutric gleysol as shown in Table 1.

Forty five field vane shear measurements were conducted on each of the 9 plots with 3 (Fig. 2a, b) different treatments representing a wide spectrum of Soil Moisture Content (SMC) values that are prevalent in the field during tillage practices. Plots G, H and I were subjected to SMC of

Table 1: Some physical and chemical properties of a sandy loam soil (Eutric leptosol) from the Research and Demonstration Farm, Department of Agricultural Sciences, University of Juba (CNRES, 2015)

Parameters	Values
Soil mapping unit* Eutric leptosol	
USDA texture classification sandy loam	
Drainage class (0-0.5%) moderately well	
Sand (average)	48.91
Silt (average)	43.67
Clay (average)	7.42
pH (LaMotte STH test method)	7.0
Bulk density (gm cm^{-3})	1.34
Humus content	2.95%
Plastic limit, P_L	16.6%
Liquid limit, L_L	39.0%
Plastic index, P_I	22.4

*Harmonized World Soil Data Viewer Version 1.2

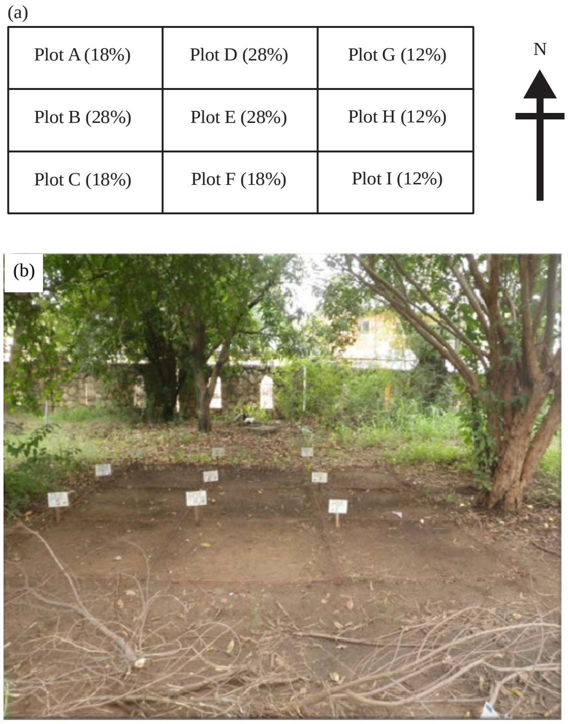

Fig. 2(a-b): (a) Experimental field with the nine plots with the different soil moisture contents at the Research and Demonstration Farm, Department of Agricultural Sciences, University of Juba and (b) Experimental site with the nine subdivided plots

Fig. 3: Eijkelkamp Theta moisture sensor attached to the penetrologger display to read out real time soil moisture content

between 10-14% (on average 12%), plots A, C and F were subjected to SMC between 15-20% (on average 18%), while plots B, D and E were subjected to SMC of between 20-35% (on average 28%).

Prior to shearing, 5 points on each of the different plots were randomly chosen and the SMC measured using a 4-pin Theta moisture sensor (Eijkelkamp agrisearch) (Fig. 3) and read out on the Penetrologger display attached to the Theta moisture sensor. For easy experimental purposes, only the average SMC values were considered. On each of the different experimental plots, three shearing velocities of 5, 10 and 20 sec for each 0.1 kg cm^{-2} shearing resistance of the graduated vane tester were applied. These applied rates correspond to shearing velocities of 7.2, 3.6 and 1.8° sec^{-1}, respectively. All field measurements and test procedures were taken using the pocket vane tester CL100 (Eijkelkamp agriSearch) with measuring range of up to 250 kPa or 2.5 kg cm^{-2}.

For each complete revolution of the CL100 device, the value was factored by 1.0936. The vane tester was adjusted so that the reference pointer was set at zero. It was then inserted very slowly into already cleaned soil surface that was devoid of any gravel, plant roots or debris. Axial pressure was then applied ensuring that all blades were fully inserted below the soil surface, while maintaining the reference pointer still at zero. Torque was then gradually rotated clockwise to 0.1 kg cm^{-2} in 5 sec and subsequently released with again the reference pointer set at zero. Next, torque was again applied clockwise to 0.1 kg cm^{-2} in 5 sec and again released thereafter. The procedure was repeated for the predetermined shear times of 10 and 20 sec for each 0.1 kg cm^{-2} till failure was attained in line with ASTM D2573-01 Standard test Method for Field Vane Shear Test in cohesive soil. At failure, the peak undrained shear (peak S_{und}) strength was then registered in kg cm^{-2}.

Land preparation: The piece of land was first cleaned and then divided into nine plots (Fig. 2a, b), marked from A, B, C, D, E, F, G, H and I. The size of each plot was about 150×150 cm. Soil samples from the different plots after preparation were then taken to the laboratory for both chemical and physical analysis.

RESULTS AND DISCUSSION

Figure 4 showed that soil moisture content between 18-25% had both positive loading on time to failure, t_f as well as on the undrained shear strength. Conversely, the relatively low soil moisture contents below 12% had negative loading on both components. Such low SMC values less than the plastic limit (16%) would suggest that the soil grains became too brittle subsequently leading to crushing into smaller

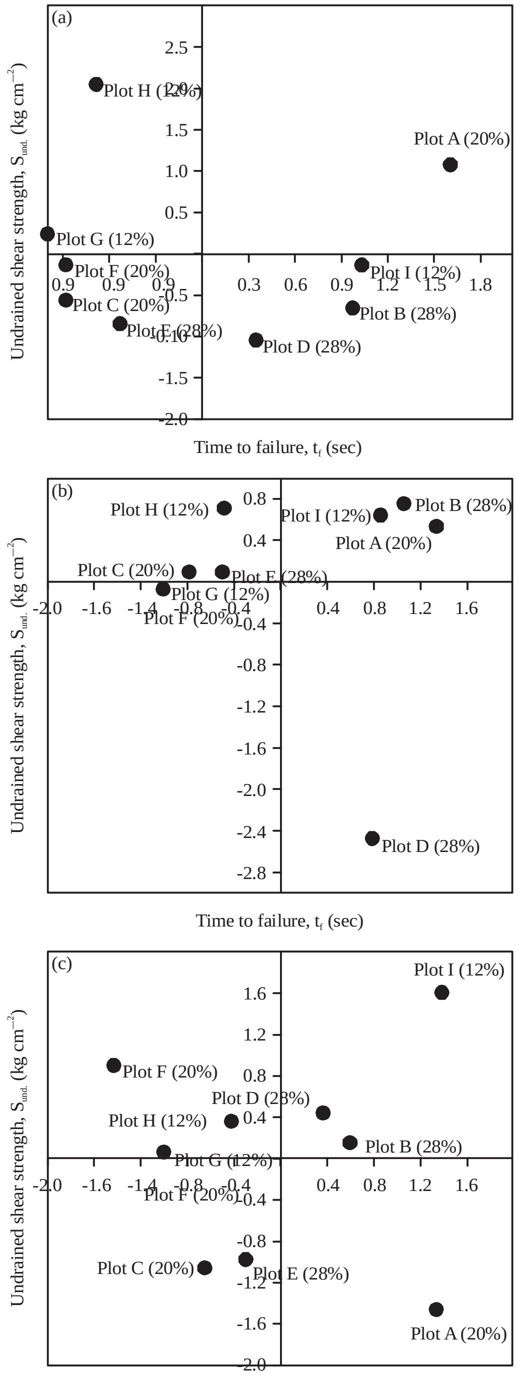

Fig. 4(a-c): Scatter plot with Eigenvalue scale showing the relationship between time to failure, t_f and undrained shear strength S_{und} in a sandy loam soil with angular shear velocities ω at (a) 7.2° sec^{-1}, (b) 3.6° sec^{-1} and (c) 1.8° sec^{-1}

grains during shearing. The significance of soil particle size on shear strength was reported by Kim and Ha (2014). Soil moisture contents close to the liquid limit range of 38% reflected more or less saturated soil conditions similar to those in soil pre-liquefaction, thereby, reducing the time to failure. It is inappropriate to account this t_f in sandy soils to pore pressure buildup per sesond as in clay soils rather, this could be attributed to inter-particle soil water that enhanced a more sliding of the soil grains against each other especially at the points of contacts (Fig. 4).

Figure 5a-c showed that t_f negatively correlated with SMC irrespective of the angular velocity ω and was best described using a power function. Although, at low $\omega = 1.8°\ sec^{-1}$ ($r^2 = 0.10$) would have enhanced some dissipation of excess pore water pressure as compared to the relatively faster $\omega = 7.2°\ sec^{-1}$ ($r^2 = 0.43$), the undrained shearing behavior under unsaturated conditions ($SMC \leq 12\%$) and that under partial or full saturation ($SMC \geq 25\text{-}36\%$ was similar. Observations on the failure times as a function of angular velocity ($t_f = f(\omega)$), showed increased t_f at low ω and vice versa for any given soil water content. It is assumed that a significant contribution to failure times was attributable to the amount of SMC encompassing the soil particles that tended to facilitate a more sliding behavior especially under partial or fully saturated conditions (Fig. 5a-c).

Figure 6a showed a negative correlation between the soil water content and the undrained shear strength S_{und}, whereas, Fig. 6b described this relationship under different SMCs, which both were best expressed by power function:

$$S_{und} = \Lambda \theta^{-\beta} \tag{7}$$

where, Λ and β are soil dependent parameters with the latter ($1 \geq \beta \geq 2$) representing the slope of the linear function between S_{und} and θ. The magnitude of S_{und} was dependent on amount of SMC. Between SMC 16-23% for example, the S_{und} was highest for soils with lower water contents than those with relatively higher water contents. Similar relationship was reported by Koumoto and Houlsby (2001). At some chosen SMC for example, the S_{und} was highest at about 0.63 kg cm^{-2} for the drier soil with average SMC at 12%, whereas, S_{und} was about 0.43 kg cm^{-2} for wetter soils with average SMC at 28%. There was a 46.5% decrease in S_{und} by a 16% increase in SMC. On average, the S_{und} varied between 0.63-0.18 kg cm^{-2}, more scattered around the P_L, while converging around L_L, respectively. The wide ranging variability at low SMCs (15-25%) correspondingly enhanced a wide ranging S_{und} perhaps due to the presence of interspersed saturated pockets within the soil matrix. With SMC increase, the soil matrix tended to be more homogenized with the SMC wholly and uniformy distributed within the soil matrix, thereby prompting a small S_{und} variability range (Fig. 6).

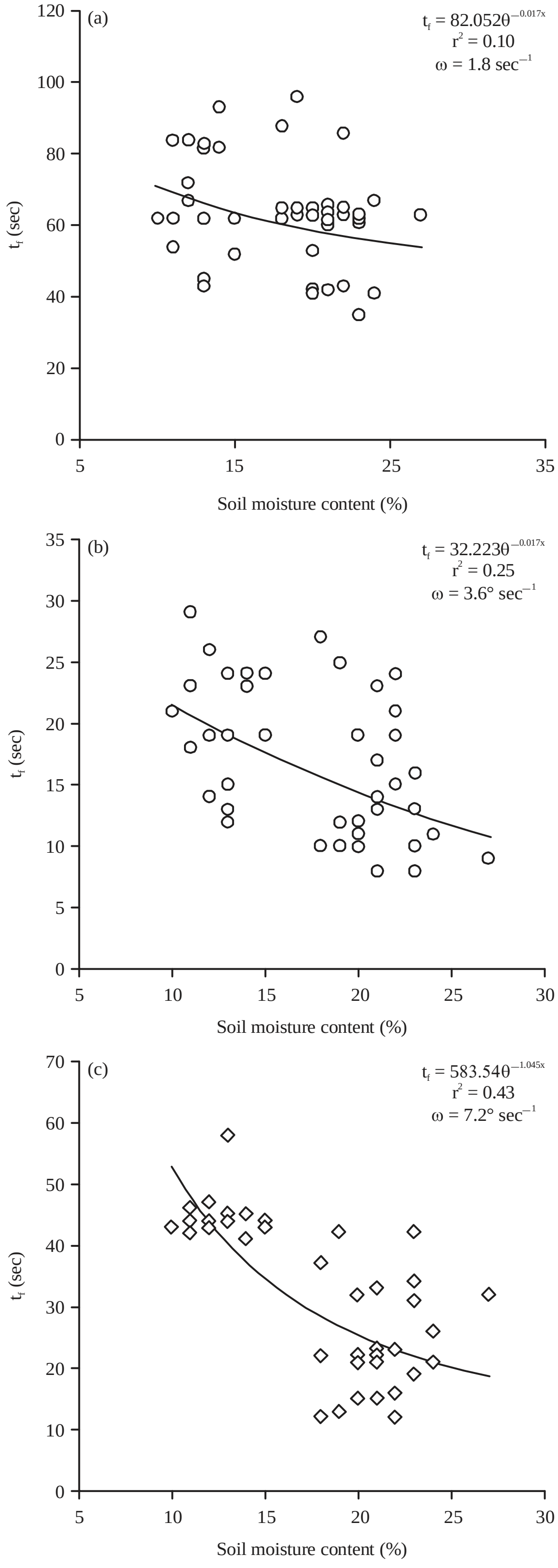

Fig. 5(a-c): Relationship between time to failure (t_f) and soil moisture content at three different angular velocities (a) 1.8° sec^{-1}, (b) 3.6° sec^{-1} and (c) 7.2° sec^{-1} in a sandy loam soil

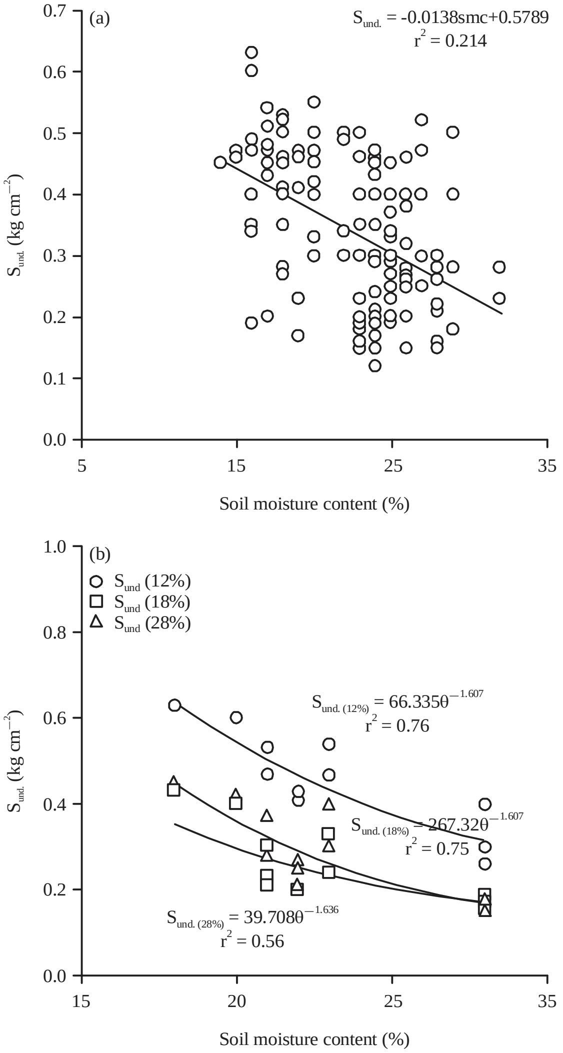

Fig. 6(a-b): (a) Relationship between SMC (%) and undrained shear strength (kg cm^{-2}) of sandy loam soil Eutric leptosol samples and (b) Relationship between soil moisture content and the undrained shear strength of a sandy loam soil Eutric leptosol samples

The SMCs varied between 10-30%, whereas, the S_{und} between 02.-0.6 kg cm^{-2} with mean value about 0.3 kg cm^{-2}. Similar studies on undrained shear strength of soils gave the S_{und} for soft soils as between 20-40 kPa and for firm soils as between 40-75 kPa. These results for the tested soil was between 20-60 kPa, which would suggest a soft to firm soil i.e., normally consolidated soil. The results of this study are in overall agreement with similar studies reported on Singapore marine clay by Robinson *et al.* (2003).

The entire dataset of all S_{und} under different soil moisture contents and angular velocities as a function of time to failure t_f is represented in Fig. 7. The results showed positive

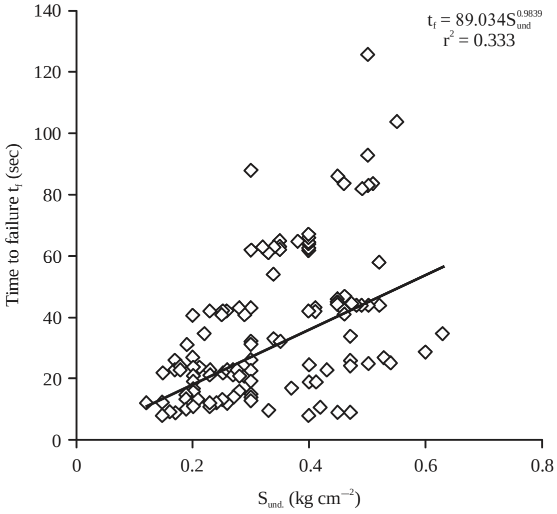

Fig. 7: Time to failure t_f, as a function of the undrained shear strength S_{und} of a sandy loam soil

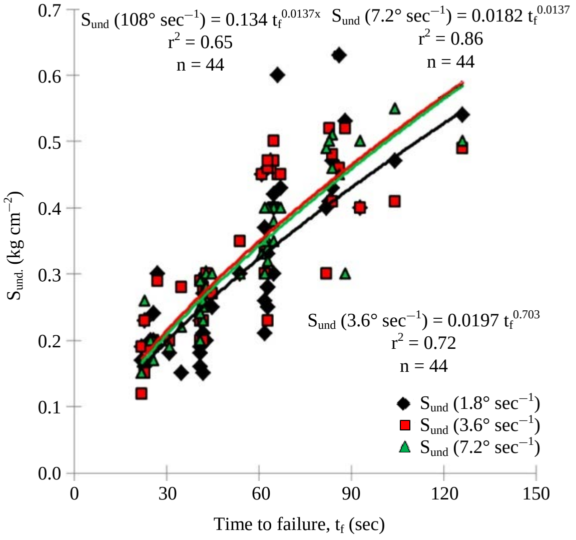

Fig. 8: Relationship between time to failure, t_f (sec) and the undrained shear strength $S_{und.}$ at three angular velocities

correlation between S_{und} and t_f and was best expressed by a power function. Generally, the S_{und} was between 0.2-0.6 kg cm^{-2} with time to failure within the first 40 sec (Fig. 7).

Figure 8 shows the time to failure t_f at three different angular velocities of 1.8, 3.6 and 7.2° sec^{-1} of each of the 45 samples. The relationship between t_f and the different angular velocities were best described by a power function as:

$$S_{(und.)(Svel)} = \vartheta t_f^{\alpha} \tag{8}$$

where, ϑ is a constant at $(0.02 \leq \vartheta \leq 0.1)$ and α is a soil dependent parameter at $(0.01 \leq \alpha \leq 0.7)$. Since part of the test objective was to understand the effects of different angular velocities conducted at the same soil moisture content, the study found out that the different angular velocities; 1.8, 3.6 and 7.2° sec^{-1} showed different times to failure t_f at 126, 56 and 35 sec, respectively. The shear strength developed on the cylindrical failure surface during shearing was equivalent to the force or torque applied and showed a positive relationship. Similar positive relationship between t_f and the undrained shear strength have been reported by O'Kelly (2013). The estimated angular rotation at failure at the different angular velocities of 1.8, 3.6 and 7.2° sec^{-1} were about 18.12, 17.94 and 19.15°, respectively (Fig. 8).

For all tested samples, it was found out that increase in ω led to decrease in S_{und}. Although, no direct inferences from SMC and its influence on pore water pressure in determining the magnitude of S_{und} in unsaturated soils, it is argued that the ω must have been influenced by the pore water pressure. Under unsaturated soil conditions, the measured SMCs in the experimented plots ranged between 12-28% and were significantly lower than the liquid limit, so that the influence of pore water pressure at the inter-particle points of contact was less significant. This meant that further increase in the rotational shear force, there occured soil particle and soil water rearrangement that inevitably led to decreased S_{und} with softening of the soil skeleton.

Rate of vane rotation and the implications on S_{und} has been reported by Perez-Foguet *et al.* (1999), who highlighted that field S_{und} was often overestimated when compared to laboratory tests. Earlier on, Bjerrum (1973) proposed a reduction of the vane measured S_{und} with respect to the plasticity index of the clay. Similar studies of the rate of rotation on S_{und} have been reported by Wiesel (1973) and Tortensson (1977), who proposed a power function between the S_{und} and angular velocity as:

$$S_{(und)\ vane} = k_1 \omega^{k_2} \tag{9}$$

where, k_1 and k_2 are constants with k_2 ranging between 0.02-0.07. From these studies (Fig. 9), the k_2 constant of the power function closest to that reported by both authors was 0.014 at angular velocity of 1.8° sec^{-1} and that k_2 values for all three measured angular velocities varied ten-fold between 0.01 and 0.7. The comparison of such k_2 values with other results is, however, difficult as this depends on several factors such as: Vane shape, size, type and state of soil. It is worth

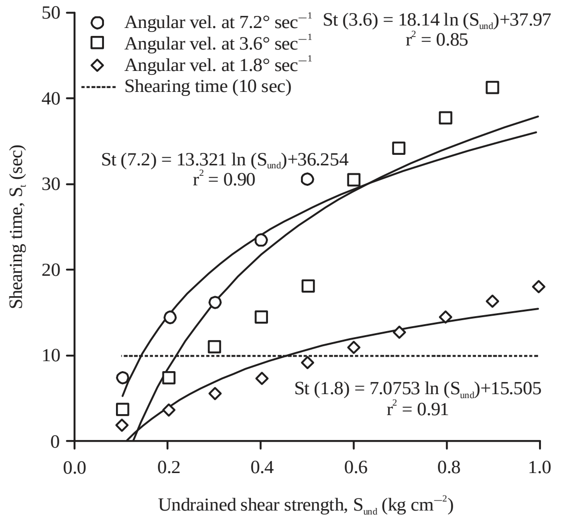

Fig. 9: Logarithmic function representing the relationship between undrained shear strength S_{und} and shearing time S_t at the different angular velocities in a sandy loam soil (Eutric leptosol)

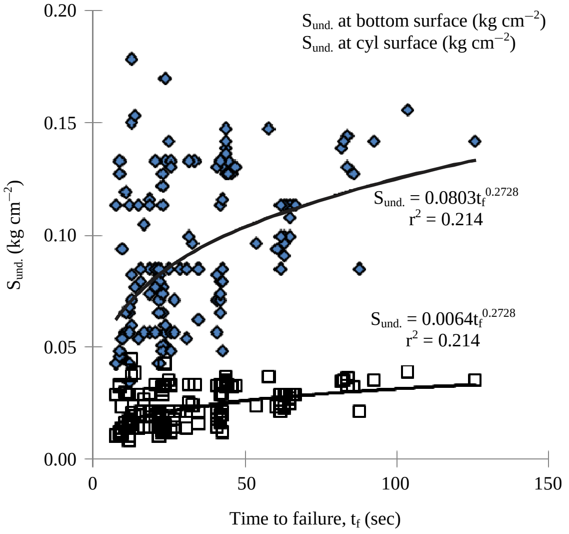

Fig. 10: Relationship between time to failure t_f and predicted undrained shear strength S_{und} at both cylindrical and bottom end surfaces of blades of the pocket vane tester

mentioning that the experimental procedures at the different angular velocities ensured that the unsaturated soil matrix was subjected to small shear strain during each shearing sequence. However, volume compression did not lead to pore-water pressure buildup as this was significantly lower that the liquid limit (L_L) of 39%. The accumulation of small radial deformations in the sandy loam soil during each cyclic shearing sequence must have led to densification and increase in particle interlocking and therefore, increase in the shearing strength and time to failure.

A better approximation of S_{und} with varying SMCs during shearing would be to treat the soil as a deformable porous medium, whose deformability depends on the amount and state of SMC. This would allow the application of constitutive laws relating to shear stresses and strains that incorporate time influence based on a visco-elastic-plastic theory. Saturated soils with $\omega \geq \omega_L$, viscous effects are considered, meanwhile under unsaturated conditions $\omega \leq \omega_{vp}$ or the visco-plastic limit. An accurate estimation of S_{und} would be the application of constitutive laws based on visco-plastic theory and compare the measured values within the SMC range of 12-35%.

The relationship between S_{und} and shearing time S_t at the different angular velocities is shown in Fig. 10. It showed a decrease in angular shear rate with increasing S_{und} and was best described by a logarithmic function. For example at $S_t = 10$ sec, the S_{und} was lowest at about 0.16 kg cm^{-2} with the highest ω at 7.2° sec^{-1}, with about 0.2 kg cm^{-2} for 3.6° sec^{-1} and about 0.45 kg cm^{-2} for the lowest ω at 1.8° sec^{-1} (Fig. 10).

However, the logarithmic function appeared to poorly describe the measured data especially at both higher S_{und} (≥ 0.5 kg cm^{-2}) and ω ($\geq 3.6°$ sec^{-1}) than at lower values. This would suggest that the S_{und} of the experimented soil is anywhere between 0.1 and 0.5 kg cm^{-2} (10-50 kPa is the average value of normally consolidated soft sandy loam/silty or clayey silts) with optimum shear velocity of 1.8° sec^{-1}. Higher angular velocity would lead to reduced particle rearrangement and interlocking and hence, lower S_{und} values. Between results are contrary to those reported by Biscontin and Pestana (1999), who found an increasing S_{und} with increasing peripheral velocity. Such comparisons, however, may be questionable due to the inherent nature of the experiment in terms of: Vane size (Chandler, 1988; Tortensson, 1977), type and shape (Silvestri *et al.*, 1998; Menzies and Merrifield, 1980), field versus laboratory test (Kirkpatrick and Khan, 1984), remolded or mixed soils; thixotrophic effects (Kimura and Saitoh, 1983), strain rates, viscous mixtures and slurried materials (Keentok *et al.*, 1985; Komamura and Huang, 1974). It can be seen that the change in S_{und} as a function of ω was about 25% between ω = 7.2 and 3.6° sec^{-1} and 125% from ω = 3.6° sec^{-1} and 1.8° sec^{-1} indicating a significant increase in S_{und} due to decrease in the ω.

Table 2: Relationship between S_{und}, angular velocity (w) and SMC of a Eutric leptosol

				$S_{und.}$ f (SMC) (kg cm^{-2})		
Angular velocity (w)	Av. SMC (%)	Av. S_{und} (kg cm^{-2})	S_{und} f (ω) (kg m^{-2})	12%	18%	28%
7.2° sec^{-1}	12	0.321	0.309	0.331	-	-
	18	0.312		-	0.318	-
	28	0.293		-	-	0.303
3.6° sec^{-1}	12	0.321	0.311	0.331	-	-
	18	0.308		-	0.318	-
	28	0.304		-	-	0.303
1.8° sec^{-1}	12	0.351	0.327	0.331	-	-
	18	0.335		-	0.318	-
	28	0.295		-	-	0.303

Av: Average

Table 3: Statistical parameters showing the resultant effect of change of ω soil moisture content and S_{und} of a sandy loam soil. (Eutric leptosol)

	Angular velocity 7.2° sec^{-1}				Angular velocity 3.6° sec^{-1}				Angular velocity 1.8° sec^{-1}			
Statistical parameters	t_f (sec)	Peak $S_{und.}$ (kg cm^{-2})	SMC (%)	Angle of rotation normal to failure plane (°)	t_f (sec)	Peak $S_{und.}$ (kg cm^{-2})	SMC (%)	Angle of rotation normal to failure plane (°)	t_f (sec)	Peak $S_{und.}$ (kg cm^{-2})	SMC (%)	Angle of rotation normal to failure plane (°)
Mean	16.156	0.311[a]	18.089	18.12	30.578	0.308[b]	18.089	17.94	55.467	0.328[c]	18.089	19.15
SD	6.793	0.127	4.362	45.847	12.259	0.109	4.362	39.334	22.662	0.112	4.362	40.304
CV	2.378	2.441	4.146	2.441	2.494	2.823	4.146	2.823	2.448	2.926	4.146	2.926
Skewness	0.538	0.729	-0.539	0.729	0.159	0.518	-0.539	0.5177	0.2178	0.344	-0.539	0.344
Kurtosis	-1.609	-0.733	-1.728	-0.733	-1.546	0.155	-1.728	-1.546	-1.155	-1.208	-1.728	-1.208

[a, b, c]Not significant at p>0.05, SD: Standard deviation, CV: Cumulative velocity

At high angular velocity (7.2° sec^{-1}), the undrained shear strength was low (S_{und} = 0.309 kg cm^{-2}), increased to 0.311 kg cm^{-2} at 3.6° sec^{-1} and finally to S_{und} = 0.327 kg cm^{-2} at angular velocity ω =1.8° sec^{-1} as in Table 2. This observation suggests that changes in the undrained shear stiffness are, by and large controlled by the moisture content in the soil matrix. Similarly, the slow rate of shear must have led to partial drainage leading to consolidation. This study also showed that the S_{und} at some given SMC, e.g., 12% was not affected by change in angular velocity which remained constant at 0.331 kg cm^{-2}, however, the S_{und} was affected, if the angular velocity were kept constant e.g., at 7.2° sec^{-1} and the SMC varied at 12, 18 and 28% subsequently decreasing at 0.331, 0.318 and 0.303 kg cm^{-2}, respectively (Table 2).

Generally, the effect of angular velocity is critical in determining and interpreting the real value of S_{und} of a given soil. Standard test sets this at 6-12° min^{-1} or 0.1-5° sec^{-1}. Our test procedure at both 1.8 and 3.6° sec^{-1} except at 7.2° sec^{-1} are clearly within that range. A comparatively lower angular velocity as at 1.8° sec^{-1} would have resulted in partial drainage and consequently led to particle rearrangement and hardening of the soil matrix as manifested by the increase in S_{und}.

Examples of measured peak S_{und} and angle of rotation to failure at the different angular velocities ω are shown in Table 3. Generally, peak S_{und} was on average 0.3 kg cm^{-2} at the different angular velocities with relatively high angle of rotation to failure (19°) at lower angular velocity (1.8° sec^{-1}). There was a slight decrease to 18° at 7.2° sec^{-1} angular velocity and then finally to17° at 3.6° sec^{-1}.

It can be said that the angles of rotation at the different angular velocities were not significantly different at p>0.05 suggesting that the angle of rotation was a direct function of the peak S_{und} i.e., $\omega = f(S_{und})$. These results showed that the angle of rotation was not influenced by neither the angular velocity nor the soil moisture content, but more by the peak S_{und}. On average, the time to failure t_f was between 16 and 55 sec with peak S_{und}-values at 0.311 and 0.328 kg cm^{-2} for fastest and slowest angular velocities, respectively.

Predictions of the shear resistance generated by the torque on both vertical and horizontal surfaces are shown in Fig. 11. The predicted shear resistance was generally low and on average 0.1 kg cm^{-2} at the vertical or cylindrical surface, whereas, at the horizontal or bottom end of the vane blade this was comparatively higher at 0.4 kg cm^{-2}.

For the time $0 \le t_f \le 50$ sec, the predicted S_{und} for the horizontal surface showed higher values than those at cylindrical surface by about 40%. The predicted torque was expressed and approximated as a function of the length of the vane blade (D-d) as:

$$T(\omega)\ \alpha \frac{1}{\sqrt{(D-d)}} \tag{10}$$

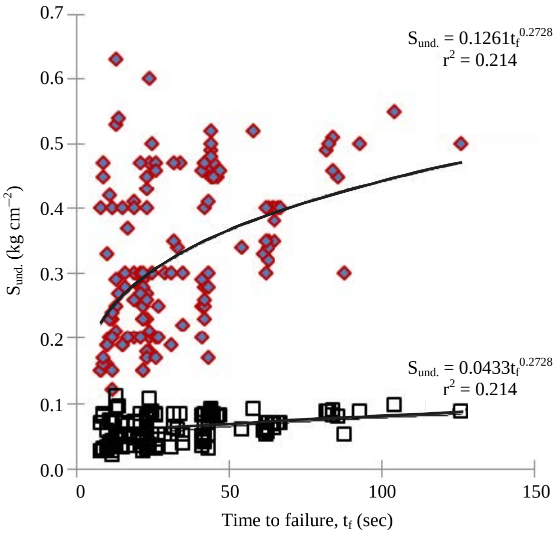

Fig. 11: Comparison of the measured shear strength and the averages generated from both cylindrical and bottom end surfaces of the vane tester

Predicted corresponding angular rotation at failure:

$$\omega_f \; \alpha \sin^{-1} \frac{1}{\sqrt{(D-d)}} \tag{11}$$

$$\omega_f \; \alpha \sin^{-1} \; T(\omega) \tag{12}$$

The angle of rotation at maximum torque independent of soil moisture content was on average about 18.69°. At lowest torque of 0.17 kg cm^{-2}, the angle of rotation was about 8.56° while at the highest torque of 0.71 kg cm^{-2} this was about 33.76°. The latter results with high torque and angle of rotation values suggested experimental irregularities and were therefore, an exception rather than the rule. The results showed that the horizontal shear resistance had a significant influence on the total maximum shear resistance generated at failure than the vertical or cylindrical shear resistance. Similarly, the results showed a wide range of progressive failure suggesting varying shear resistance forces between 0.05-0.2 kg cm^{-2} on the horizontal plane with peak failure times mostly attained within the first 50 sec. Whereas, the shear resistance in Eq. 1 at the vertical surface was more or less constant at 0.1 kg cm^{-2} on average, this was on average 0.3 kg cm^{-2} at the horizontal surface in Eq. 6. This wide ranging shear resistance values along the horizontal surface would suggest the gradual and progressive failure from the outer surface towards the center of the vane.

Figure 11 shows that the measured S_{und} varied between 0.2-0.6 kg cm^{-2} whereas, the computed value around 0.1 kg cm^{-2}. Present results showed that the computed predictions of the S_{und} were overestimated by about 40% when compared to empirical values at both cylindrical and bottom end surfaces.

The computed predictions took account of the segregated shear components whereas the empirical values were simply an aggregation of both values. According to Bjerrum (1972), this could be attributable to both viscous effects and rate of rotation.

CONCLUSION

The undrained shear strength S_{und} was performed on a sandy loam soil (Eutric leptosol) under variable shear velocities, ω and soil moisture contents representing the different traction speeds during tillage. Angular velocities at 1.8, 3.6 and 7.2° sec^{-1} negatively correlated with the undrained shear strength and were best described by a logarithmic function. Similarly, the undrained shear strength negatively correlated with soil moisture content and was best described using the exponential function.

Because under unsaturated conditions the measured soil moisture contents in the experimented plots were generally lower than the soil liquid limit, the apparent buildup of pore water pressure during shearing at the different shear velocities and soil moisture contents had no influence on both the time to failure, t_f and maximum undrained shear strength at failure. On the contrary, the time to failure t_f showed weak positive correlation though at relatively low r^2-values with increasing soil moisture content. Based on empirical and predicted results, the following conclusions can be made:

- The results of applied torque at both the cylindrical or vertical (T_v) as well as the horizontal surfaces (T_h) showed that the Eutric leptosol in its failure characteristics was anisotrophic. The T_h was greater than T_v by factor 3
- The predictions of the shear resistances using the vane tester were more reliable than empirical tests that were subject to errors and overestimation. The difference between the empirical and predicted torque ranged between 0- 40%
- The magnitude of the S_{und} was contingent on the degree of SMC that negatively correlated. S_{und} increased with decrease in SMC and vice versa
- The angular velocity (w) negatively correlated with S_{und} at constant SMC, the S_{und} remained constant irrespective of change in angular velocity
- The time to failure, t_f positively correlated with S_{und} independent of change in angular velocity

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