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Soil Failures Under Rigid-Tracked Forestry Machines as a Function of Slope and Soil Wetness

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Abstract: *Forestry machines are at greatest risk of sliding on steep slopes when soils are essentially saturated. In soil mechanics, this situation is defined as the $\phi=0$ condition. Values of $c(\phi=0)$ were calculated for a western Oregon forest soil from previously published data and soil water potentials wetter than -10 kPa. The distribution of pressure and soil contact for a rigid-track were calculated and combined with values of $c(\phi=0)$ to determine the net soil resistance. The value of $c(\phi=0)$ at saturation ratios of 0.8, 0.7, and 0.6, were 87, 155, and 287 kPa, respectively. As the value of $c(\phi=0)$ decreased, an uncontrolled, sliding failure was estimated to occur at slopes between -39 and -67 percent. When average track pressure and $c(\phi=0)$ were equal, a sliding failure was expected at a slope of -29 percent. Terramechanics models and coefficient of friction do not apply to track-soil interactions in the $\phi=0$ condition.*

Keywords: ϕ=0 condition, terramechanics, coefficient of friction, unsaturated soil mechanics

1. Introduction

Using ground-based harvesting equipment on steep slopes is becoming more common because it is safer for workers and generally less expensive than cable systems (Visser and Stampfer 2015). Hence, operating large, rigid-tracked harvesting machines on steep slopes, with or without tethering, are becoming the preferred method of harvesting in mountainous terrain, especially in western North America and New Zealand (Sessions et al. 2017; Visser and Berkett 2015). Loss of traction on steep slopes is a major issue because of the risk of machines sliding downslope and turning over (Visser and Stampfer 2015). Turning, high slip, and repeated passes of ridge-tracked machines on steep slopes often destroys the tractive support of the slash mat and forest floor, as well as the underlying root mat, which results in a machine becoming dependent on the shear strength of the soil at the track-soil interface.

Soil wetness and slope are the two factors dominating soil shear strength at the track-soil interface. It is this complex interaction that determines the risk of a machine sliding downslope. There are currently two approaches to estimating the impact of soil wetness on a soil's resistance: 1) reducing the coefficient of friction, CoF, for wet soils (Hittenbeck, J. 2013; Visser and Stampfer 2015); and 2) using Bekker's (1962) terramechanics models of machine, soil, and slip-sinkage relationships (Sessions et a. 2017; Belart et al. 2019). These approaches are not valid when the soil at the track-soil interface is saturated, or becomes essentially saturated when the soil at the track-soil interface is compacted. Essentially saturated soils are common because some air is trapped in the pores of compacted soil. Two examples are: the separation between a soil compaction curve and the zero air voids line in soil compaction test; and the low air-filled porosity of soil after forestry machines traffic wet soils (McNabb et al. 2001).

1.1 Objective

The objective is to describe the soil mechanics of machine-soil failure for a rigid-tracked feller-buncher operating on wet soil that is compacted until the soil is essentially saturated. An example of soil failures will be given using the machine specifications recently published by Sessions et al. (2017), and adaptation of surface forest soil shear strength and a consolidation/compressibility model for different soil densities and wetness for an interior Coast Range forest soil in western Oregon (McNabb and Boersma 1993, 1996).

1.2 Background

Bekker's (1962) terramechanics models were primarily developed using lateral earth pressure theory from foundation engineering, but applied it to top soils (Reece 1964). Bekker also developed his own instruments and protocols for measuring soil strength, which could also be used in the field. He reported soil strength as having two components: cohesion, c, and a frictional component, ϕ. The simple equation to described soil strength is

$$\tau = c + \sigma * \tan \phi, \qquad (1)$$

where τ is soil strength and σ is the normal force. The equation is the same as used in soil engineering; hence, Bekker also used soil engineering concepts to describe the soil failure process. In Equation 1, the normal force acts perpendicular to the slope while shear force acts perpendicular to the normal force. Hence, soil strength becomes a soil resistance force acting parallel to the slope.

In soil engineering, the values of c and ϕ are obtained by conducting soil engineering tests on several samples of the same soil at increasing initial values of σ. These tests are only done on drained undisturbed soil cores or when the values of σ have been corrected for changes pore water pressure (Das 2013). In a triaxial test, the test of each sample is defined by a Mohrs circle (dashed lines, Fig 1). The dashed line tangent to a series of increasing Mohrs circles defines the shear strength of the soil at failure. The cohesive value of soil strength, c, is defined as the intercept of the failure line when σ is zero. The slope of the dashed line is the angle of internal friction, ϕ. To clarify the ambiguity between the different values of c and ϕ obtained in soil engineering tests and his terramechanics measures of soil strength, Bekker (1969) later stated unequivocally that it was unwarranted to assume that values of soil strength obtained with a bevameter were the same as those obtained using soil engineering tests. Clay soil mixtures, and particularly natural clay soils, were also poorly represented in the development of terramechanics models. Consequently, soil wetness was also poorly integrated into his models. Hence, it soon became a common practice to reduce the value of ϕ to represent the shear strength of wet clay soils in terramechanics models (Reece 1964). This practice continues to be done (Sessions et al. 2017; Belart et al. 2019). Values of ϕ as low as 6 degrees have been used for forest soils when the values of ϕ for saturated forest soils in the Pacific Northwest obtained using soil engineering tests are greater than 30 degrees (Schroeder and Alto 1983; McNabb and Boersma 1993).

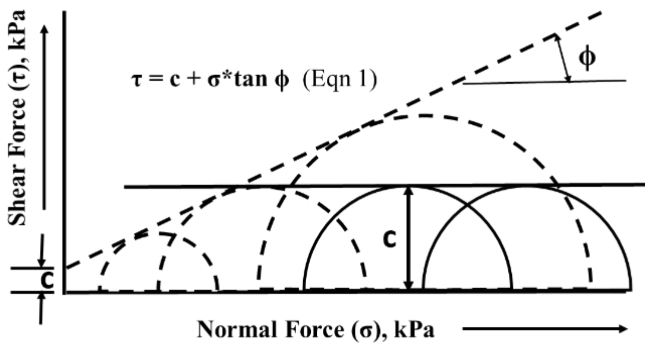

Fig 1. Mohrs circles and soil failure line (dashed lines) for drained soil strength, Eqn 1, and for unconsolidated-undrained tests of saturated soil (solid lines, Eqn 2)

Bekker (1962) focused exclusively on drained soils because his models included a sinkage component, but it is not clear how much was due to compressibility, compaction, of the soil versus soil displacement. Only twice was ϕ mentioned as having a value of zero and it was with regards to ideally plastic clays and snow. At which time, the shear strength was defined as being equal to c

$$\tau = c. \qquad (2)$$

Wong (2008) later reinforced the point that Eqn 1 did not apply to saturated clay soils. For the latter soils, Eqn 2 applied but with minimal elaboration. His explanation for focussing on Eqn 1 was that "…most of the trafficable earth surface generally have both cohesive and frictional properties…".

The values of c in Eqn 1 cannot be used in Eqn 2; however, only Reece (1964) explicitly state that a quick-test (an unconsolidated-undrained triaxial test) was the appropriate method for defining c when clay soils are saturated. This test is also referred to as the ϕ=0 condition. In an unconsolidated-undrained triaxial tests, the soil density remains constant in the absence of drainage and the grain-to-grain soil contacts responsible for soil strength remains unaffected (Mitchell 1976). Hence, the value of soil strength I the ϕ=0 condition is also constant.

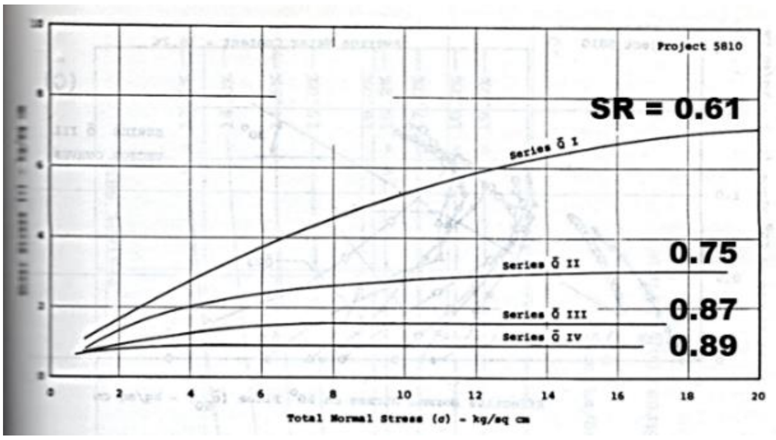

Fig 2. Failure curves as a function of τ (y axis) and σ (horizontal axis) for wet, partly saturated soils at four saturation ratios (Casagrande and Hirschfeld 1960)

Casagrande and Hirschfeld (1960) confirmed that compression of a soil at high saturation ratios can produce the ϕ=0 condition (Fig 2). In their example, curves were fit to several Mohrs circles, which showed τ as a function of σ (Fig 2). The value of τ initially increased with the increase in σ until the air in the soil had been compressed to a saturation ratio, SR, approaching 1. SR is a measure of relative amount of air-filled-pore space in a soil, and the total volume of soil voids. At such time, the curve became asymptotic; this is indicative of the ϕ=0 condition. The ϕ=0 condition is also illustrated in Figure 1 as a series of Mohrs circle of the same diameters (solid lines). Hence, soil strength in the ϕ=0 condition is the radius of the Mohrs circles, which is the value of cohesion, c(ϕ=0) that must be used in Eqn 2. Furthermore, Eqn 2 is only used when a soil is saturated, or is essentially saturated. The latter same condition also applies to wheels or tracks compacting a wet soil until only trapped air remains (McNabb et al. 2001).

Based on the example of Casagrande and Hirschfeld (1960), as the saturation ratio, SR, decreases, the inherent soil strength of the initially drier soil requires a larger value of σ to compress the soil until the curve become asymptotic (Fig 2). As a result, soils of a lower SR will have higher values of c(ϕ=0) as long as the soil remains essentially saturated. An example of how a series of Mohrs circles at different SRs, which had been compressed until essentially saturated, would appear relative to the drained shear strength at failure line is shown in Figure 3.

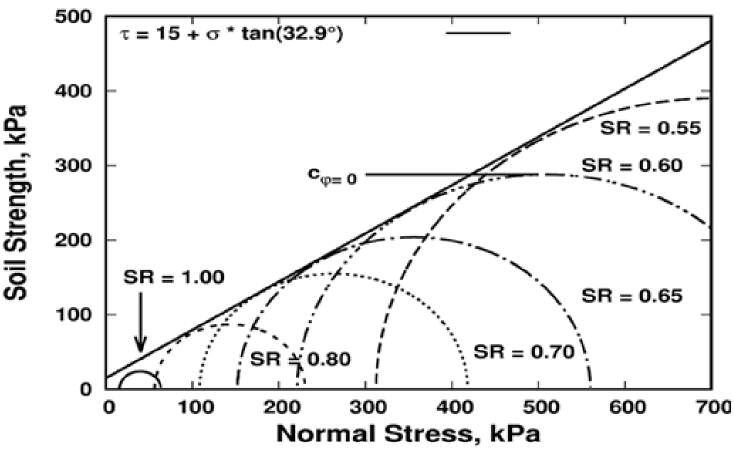

Fig 3. The c(ϕ=0) values of soil strength for an essentially saturated soil compressed at a initial SR between 0.55 and 1

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2. Materials and Methods

The values of c(ϕ=0) for a range of saturation ratios was estimated for a soil similar to the soil for which Belart et al. (2019) reported a rigid-track harvester had slid down a 38 percent slope in western Oregon. Five values of c(ϕ=0) were estimated for the Jory soil based on a nonlinear model of soil density as a function of normal stress and saturation ratio, the drained shear strength of saturated soil, and the volume-weight relationships among soil density, specific gravity, soil water content, and air-filled porosity of the Jory (McNabb and Boersma 1993, 1996; Das 2013). The Jory soil is a clayey, mixed, mesic Xeric Haplohumult; it is a mature soil found in the lower foothills along the east side of the Coast Range Mountains in western Oregon. The soil is a clay loam and classified as an MH. The undisturbed soil density was 0.992 Mg/m^3, and had a specific gravity of 2.44 Mg/m^3. At a soil water potential of -10kPa, soil water content was 0.30 Mg/Mg, and had a saturation ratio of 0.58.

Undisturbed soil cores had been collected from the 7-12 cm depth, which was near the middle of the topsoil horizons; soil water content ranged from nearly saturated to dry when collected. A nonlinear model of soil density as a function on σ and SR was developed from one-dimensional consolidation tests (n=140, McNabb and Boersma 1996). Twenty-three of the samples were saturated and subsequently used in a direct shear test to measure the drained shear strength: c was 15 kPa, and ϕ was 32.9° (McNabb and Boersma 1993), For the five values of SR, in Fig 3, σ was estimated by calculating the soil density at which the soil would be essentially saturated soil for the respective SR. The value of τ for each value of σ was estimated from the drained soil shear strength, and the c(ϕ=0) of soil strength estimated from the Mohrs circle and soil strength relationships in Fig 1.

The maximum force exerted pm the leading and trailing edge of the rigid-track, and length of track in contact with the soil were recalculated for these analyses using the same machine dimensions and weight of a feller-buncher as Sessions et al. (2017). For a rigid track, the change in force along the length of the track in contact with the soil was assumed to be linear (Reece 1964).

When the track pressures were all less than the c(ϕ=0) value of soil strength, a stationary machine had not fully engaged the available soil strength and was not in the ϕ=0 condition. Whenever the track pressure was greater than the c(ϕ=0) value of soil strength, the track-soil interface along that length of track was assumed to be in failure. For all track force less than the c(ϕ=0) value of soil strength, the machine was not fully engaging the available soil strength, and when values of all track force were greater than c(ϕ=0). All three factors decrease the stability of the machine.

3. Results

A rigid-track feller-buncher exerts an eccentric force on the soil when the boom, stick, and felling head without out a tree is fully extended (Sessions et al. 2917). In this configuration and on level terrain, the rear edge of the track is not applying force to the soil (Fig 4). When oriented down-slope, the maximum force exerted by the front edge of the track increases several-fold. During uphill travel, the distribution of force on the soil is nearly constant as a slope of +50 percent. These are all static forces on the soil, which changes when the machine is working to fell trees or thrust is required to move on the slope (Lysne and Burditt 1983).

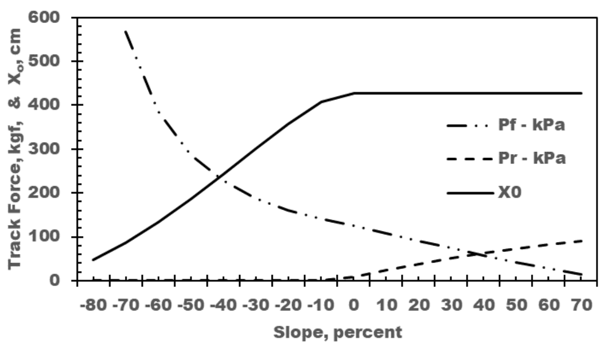

Fig 4. Maximum track force at front, P_f, and rear, P_r, edge of track, and length of track, X_0, in contact with soil as a function of slope for an untethered machine

The increase in soil density as a result of compression of unsaturated soil is seldom a consideration when the shear strength of soil is calculated (Fig 1). However, an increase in soil density is required for increasing grain-to-grain contact required to increase soil

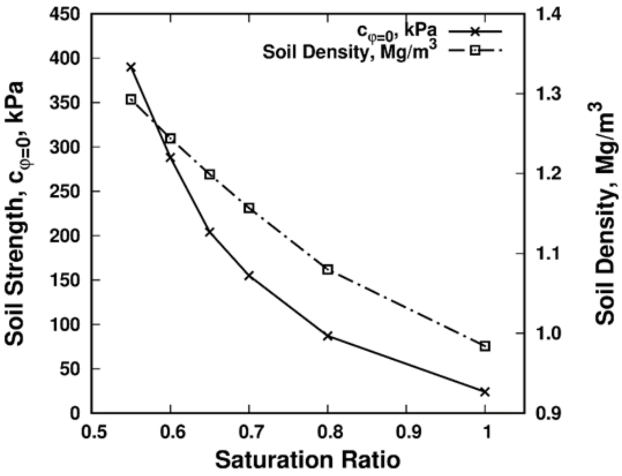

Fig 5. Soil strength, cϕ=0, and soil density as a function of the saturation ratio

strength (Mitchell 1976; McNabb and Boersma 1993). For unsaturated soil, compaction to increase soil strength and how soil density is limited by a lack of air-filled-porosity in wet soil is well understood. For the Jory soil, the soil density increased approximately in proportion to the decrease in saturation ratio (Fig 5). More importantly, the increase in the c(ϕ=0) value of soil strength increased exponentially as SR decreased. This increase occurred for a small range of soil water potentials (-10 to 0 kPa). A free-to-drain soil would be expected to drain to about -10 kPa in two days (McNabb et al. 2001). This range of soil water potential coupled with the range of saturation ratio would have had a minimal impacted on the soil strength un saturated soil (Bishop and Blight 1963). Hence, the increased in soil density is the dominant factor responsible for the increase in soil strength, but the increase is always limited by the air-filled porosity of the soil at the time of trafficking.

Bekker (1962) and Wong (2008) recognized the following equation as quantifying the maximum thrust, or total soil resistance, that wet soil could provide

$$TSR = c(\phi=0) * 2 * W * L \qquad (3)$$

where L is track length and W is the width of one track; the value of soil strength has to be c(ϕ=0), and not c used in Eqn 1. TSR is also the maximum soil resistance preventing a machine from sliding downslope. TSR will frequently have to be reduced for the wide range of forces that exist at the track-soil interface because of machine geometry and slope (Fig 4), and for the effect that differences in soil wetness has on c(ϕ=0) (Fig 5). As a result, three scenarios are required to calculate the amount of the c(ϕ=0) soil strength that the area of track in contact with the soil engages (Fig 6). The direction of travel and slope were the two additional site-specific factors determining the value of the engaged soil resistance, ESR_i, for each value of c(ϕ=0). The three scenarios are: a) track pressures less than c(ϕ=0); b) track in full contact with the soil but the pressure under one section of the track exceeded c(ϕ=0); and c) only part of the track was in contact with the soil and consequently, the track force exceeded c(ϕ=0) (Fig 6).The correct scenario ultimately depends on the direction of travel, felling head extension, slope steepness, and how the track force interacts with the value of c(ϕ=0). When the track is not fully in contact with the soil, L is preplaced with the length, X_0 (Fig 6c).

The engaged soil resistance, ESRi, is the amount of the total soil resistance that the track can engage. The unengaged soil resistance, USR, is the amount of the TSR that the machine does not engage when the track force is less than the value of c(ϕ=0) (Fig 6a). In this situation, the USR can be used for the work and movement of the machine. USR also occurs when the track force are eccentrically distributed and some values of force is less than the value of c(ϕ=0) (Fig 6b,c). This USR may only be engaged if some minor sinkage of the track occurs in a stationary position.

The line defined by ‘be’ in Figures 6b,c is the length of track where the track-soil interface is in a state of failure. This failure plane is at the bottom edge of the grousers. Another way of thinking of the track-soil failure plane is conceptually similar to a shallow translational landside where the machine acts as a surcharge on the shallow failure plane. However, as a surcharge on the failure plane, the track force greater than c(ϕ=0) is an unengaged machine force, $UMF_{b,c}$. The original machine downslope force, M_τ, assumes that the machine normal force M_σ, is fully engaging the total soil resistance. This does not occur in the ϕ=0 condition because the value of c(ϕ=0) is constant and excess M_σ produces an additional downslope force. The excess M_σ is the $UMF_{b,c}$ in Figure 6b,c.

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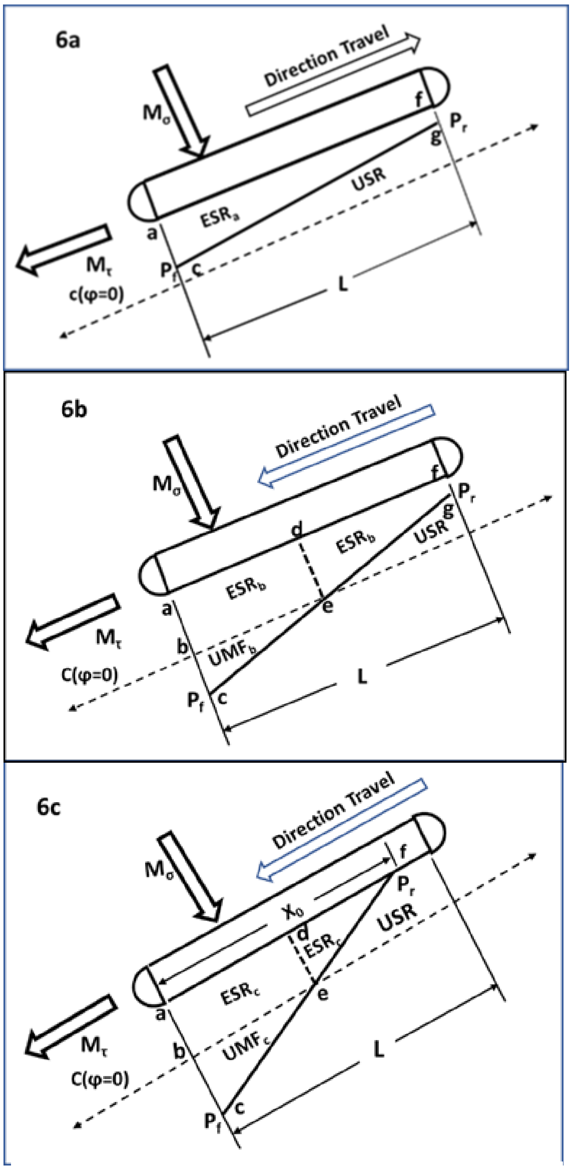

Fig 6. Diagrams illustrating the three scenarios for the track pressure-soil resistance c(ϕ=0) interface

The average track pressure of this machine is approximately 67 kPa. For an initially saturated soil, no increase in soil density is possible; hence, a c(ϕ=0) value of 67 kPa results in the minimum slope angle for this machine to slide of -29 percent. However, at a c(ϕ=o) of 67 kPa, the machine would be immobile regardless of slope because of the eccentric distribution of track pressures (Fig 4). This machine will not be stable on slopes over -65 degrees regardless of whether c(ϕ=0) is higher because of the small area of track in contract with the soil (Fig 4). Belart et al. (2019) recently reported that a feller-buncher of this size slid downslope on a soil similar to this soil at a slope of -38 percent.

Whenever the sum Mτ and the downslope component of UMF are greater than the engaged soil resistance, ESR, the machine is assumed to be in a state of a sliding, bare earth failure. The sliding of a machine also assumes that the forest floor and root system is no longer able to provide additional soil resistance because it has been removed or damage by previous track slip. Therefore, a machine sliding on bare earth is the worst-case scenario, which results following high wheel or track slip.

The difference between ESRi and the sum of the downslope forces is the net soil resistance, NSR. When the value of NSR is negative, the machine is assumed to be in a state of a machine sliding failure at the track-soil interface. For values of c(ϕ=0) of 87, 155, and 287 kPa, the corresponding slope angles at which the ESR is equal to the downslope forces are -39, -56, and -67 percent, respectively (Fig 7). A machine can be quasi-stable at slightly lower angles if sinkage of the machine is able to engage some of the USR, but any movement or rocking of the machine could readily disengage the USR thereby causing a machine to slide. Whenever a machine starts to slip, the machine is assumed to disengage from the USR, regardless. This disengagement process for an untethered machine is probably responsible for a machine accelerating downslope once a stationary machine starts to slip. Such acceleration contributes to the momentum that a sliding machine needs to plow through slash, forest floor and tree roots further down the slope.

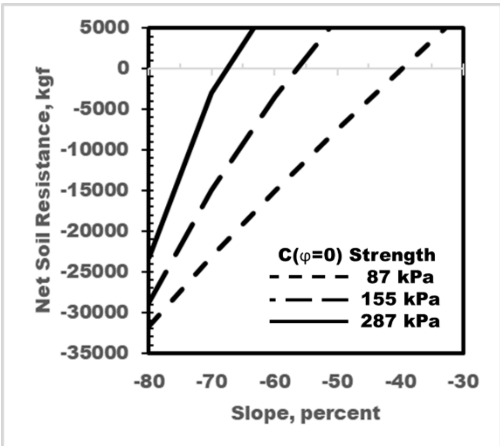

Fig 7. Net soil resistance is dependent on the c(ϕ=0) value of soil strength and slope when traveling downslope. Negatives values are indicative of a sliding failure.

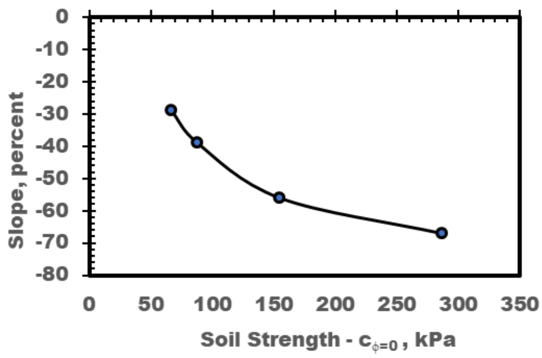

Fig 8. Downslope travel as a function of c(ϕ=0) when a sliding failure is anticipated

The NSR for an untethered feller-buncher operating on a wet soil at a SR of 0.80 is approximately -19 Mgf at a slope of -65 percent (Fig 7). On uneven terrain or when going over a stump or windfall, the slope may temporarily increase to -75 percent or more. At a slope of -75 percent, the NSR is approximately -28 Mgf. The values of NSR tend to converge for downslope operations on the steepest slopes, because the length at track able to engage the soil resistance is small (Fig 4). The value of NSR in the ϕ=0 condition also is the magnitude of the restraining force that tethering machines and associated cable systems must provide to stabilize a machine on a steep, wet soil. Additional force is required to allow the machine to effectively move and work.

4. Discussion

The $c_{\phi=0}$ values of soil strength have not been measured in surface soils because the engineering design requirements for this specific measure of soil strength is generally only measured when positive pore water pressures are anticipated on construction projects at depths of 2 to 20 m (Vardanega and Bolton 2011). Unfortunately, Reece (1964) was the only person that recognized saturated cohesive soils required a different method for measuring the cohesive strength of soil. These results confirm that the value of c(ϕ=0) increases exponentially with decreasing saturation ratio (Fig 5). While soil density is responsible for the increase in soil strength, soil density is not a particularly reliable method for quantifying the increases in the value of c(ϕ=0). For a SR of 0.80, soil density only increased about 10 percent; hence, small increases in soil density could be indicative of a soil at high risk of failure, but only if the ϕ=0 condition can be assumed. Furthermore, the feasibility of collecting a sufficient number of samples to reliably analyze soil density in this situation is very low (McNabb et al. 2001).

The ability to engage the USR is uncertain on steeper slopes. The engagement and effectiveness of the USR is most likely associated with maintaining an intact forest floor, and its relationship in maintaining an intact root system. Hence, maintaining the forest floor has many ecological and operational values. Deep slash mats and forest floors effectively spread track forces over a larger area of mineral soil, which significantly reduces the peak values of track pressures transferred to the underlying soil surface (Labelle et. al. 2015). Reducing the maximum values of track pressure on soil reduces the unengaged machine force on soil, which is an important factor reducing machine stability (Fig 6b,c). Soil strength is also increased by the root network (Wu 2013). Hence, terramechanics models that assume high slip is of value in increasing soil traction (Bekker (1962; 1969) can readily destroy the added value that the forest floor and root system have for increasing the effective soil resistance. Finally, sinkage of a track is highest at the point where the track force on the soil is highest (Reece 1964). For the feller-buncher, this is the leading edge of the track when operating downslope (Fig 4). If the machine starts to slide, the rear section of the track is expected to disengage from the USR because the leading edge of the track as already compacted the soil. Hence, c(ϕ=0) values of soil strength without consideration of the USR have been used for estimating the risk of soil failures because a bare earth failure is assumed to be the worst-case situation.

In the ϕ=0 condition, the failure plane is assumed to occur at the grouser edge of the track-soil interface, because grousers will sink quickly and fill with the soft soil. After working with a model tracked machine, Reece (1964) questioned the use of the Rankine geometry of soil strength and displacement in terramechanics models. Field experience concurs with his observations as well. The increases in soil density with increasing soil depth (McNabb et al. 2001) would also increase soil strength, which should also focus the location of the failure plane to a thin layer of soil below the grouser edge. Hence, the failure plane when a machine is sliding could be as thin as 1 cm.

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Negative soil water potentials have long been an important parameter added to Eqn 1 when calculating the effect that changes in soil water content have on unsaturated, soil strength (Bishop and Blight 1963). Unfortunately, the related theories have not been refined enough to be used to solve many practical problems (Lu et al. 2014), such as this problem. An important issue is the approach does not consider how soil water potential and soil compaction interact to affect unsaturated soil strength. The measurement of soil water potential in the field with a handheld tensiometer has confirmed when soils were drier than about -15 kPa, forest soils were not significantly compacted by wide-tire skidder (McNabb et al. 2001). However, tensiometers are less likely to be sensitive enough to measure the small differences in the range of -10 to 0 kPa that these data show are important. Furthermore, values of soil water potentials are not easily related to the air-filled-porosity of soils.

The angle of internal friction of 32.9° for the Jory soil is high compared to other cohesive soils (Mitchell 1976). Hence, values of c(ϕ=0) for the Jory increases at a faster rate as the saturation ratio decreases (Fig 3) than the value will when weaker soils are compacted across the same range of saturation ratio. Therefore, the inherent drained shear strength of soil is an important factor determining the c(ϕ=0) value of soil strength. An equally important factor according to these data is the effect that the decreasing saturation ratio has on the value of c(ϕ=0) (Fig 5). How saturation ratios of different soils vary at soil water potentials is wetter than -10 kPa is poorly understood, and several components are required to measure it.

The measurement of air-filled-porosity, units are m^3/m^3, is proposed at the most efficient and effective method of assessing the impact of changing soil wetness on the value of c(ϕ=0). However, air-filled-porosity of soil is rarely measured (McNabb et al. 2001). Higher the air-filled-porosities will allow the wet soil to be compacted to a higher soil density, and consequently, a higher value of c(ϕ=0). Most importantly, air-filled porosity can easily be measure in the field, the mean values of air-filled-porosity are much smaller than those for soil density, and their standard errors of measurement are lower than for soil density (McNabb et al. 2001).

The ϕ=0 condition is also responsible, or a major contributing factor, for machines causing deep ruts on level terrain, particularly those ruts that develop after as few as one pass of a machine. Deeper ruts will quickly form in soils with minimal differentiation among horizons when the value of c(ϕ=0) remains relatively constant with increasing depth, or drier soil is encountered. These types of ruts are a form of bearing capacity soil failure (McNabb 1993), and more precisely defined as a punching soil failure (Vesic 1963; Das 2013). In soil engineering, punching soil failures produce minimal lateral displacement of the soil. In forest operations, the soil displaced by skidder wheels rises upward along the sidewall of the tire, and a relatively intact forest floor can sometime be found in the bottom of the rut after one pass. These types of ruts are appropriated described as bearing capacity ruts in contrast to ruts developing from many cycles of wheel or track slip and sinkage. Managing operations to reduce the latter is probably more likely.

Changing terrain, soil, and weather become important issues affecting machine mobility, operability, and stability when air-filled-porosity of wet soil limits the compaction required to increase soil strength in the ϕ=0 condition. The interaction of precipitation amount and frequency with terrain and soil are the primary issue. Although overland flow seldom occurs on the surface of most undisturbed forest soils, the downslope, saturated flow of water in and over one or more mineral soil horizons is common. Anytime there is a temporary, saturated zone in a soil profile (perched watertable), there is also a phreatic zone of water extending upward at a decreasing saturation ratio. These two factors increase the risk of ϕ=0 conditions developing during and after precipitation or in areas where water will accumulate within a harvest block. Therefore, on-site tracking of rainfall is obviously an important management option to help assess the risk of when ϕ=0 conditions are most likely to occur. The dynamic impact of the frequency and duration of precipitation on the development and duration of ϕ=0 conditions in a soil, make developing a risk rating system for machine sliding on slopes based on a fixed set of slope classes unworkable. However, more complex rating systems to include terrain, soil, recent precipitation, and hillslope hydrology are possible but require testing (McNabb, unpublished).

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The coefficient of friction also does not apply to the machine trafficking of soil when the ϕ=0 condition exists. During the ϕ=0 condition, soil strength at the track-soil interface is constant and total soil resistance is defined by Eqn 3 (Bekker 1969; Wong 2008). This is in contrast to CoF, which is based on Eqn 1. CoF is simply the ratio of τ/σ, or the tangent of ϕ. Therefore, CoF only applies to drained soil where soil resistance increases in direct proportion to the force applied to the soil. Most important, CoF applies regardless of the distribution of force under the track or wheel, and regardless of whether the track or wheel are in contact with the soil. In the ϕ=0 condition, track pressure at the track-soil interface is required to engage the TSR (Fig 6a). This seldom occurs when there is an eccentric distribution of pressure under a rigid track (Fig 4). As a result, the effective soil resistance is generally less than TSR because it is reduced for areas where track force is less than c(ϕ=0), and the downslope force increases when the force is greater than c(ϕ=0). Both factors reduce machine stability on steep slopes.

5. Conclusions

Trafficking of wet soil by forestry machines often compacts the soil until it is essentially saturated, and no further increase in soil density or strength is possible. In a soil mechanics context, this situation is defined as the ϕ=0 condition. The ϕ=0 condition is unique because it produces a single value of soil strength, c(ϕ=0), that is independent of the forces exerted on the soil. The value of c(ϕ=0) is dynamic for a specific soil because deceases in the initial air-filled-porosity with the drying of soil allows the soil to be compacted to a higher value of c(ϕ=0). The ϕ=0 condition only applies as long as the soil remains essentially saturated. Therefore, the value of c(ϕ=0) and area of track-soil contact determines the effective soil resistance to a machine sliding on steeper slopes. When any point at the track-soil interface is less than or greater than the c(ϕ=0) value of soil strength, the stability of a machine decreases. As a result, the slope at which a forestry machine is at risk of sliding on bare earth depends on the eccentric distribution of force along the bottom of the track as the slope angle changes and the value of c(ϕ=0). Hence, a specific slope angle can not be specified for when a machine is at risk of sliding because of the effects that weather, soil and terrain has on air-filled-porosity. Unfortunately, this introduces considerable uncertainty as to the stability of untethered rigid-track machine on wet soils, and risk of sliding can not be defined by a set range of slope classes. The downslope forces produced by a machine on steep slopes and soils with low values of c(ϕ=0) exerts a high force on tethering machines and cables, which increases the risk of these systems failing as well.

When a machine is operating on a soil in the ϕ=0 condition, terramechanics models and values of the coefficient of traction are invalid because they are based on soil strength parameters, c and ϕ (Eqn 1), for drained soil.

6. References

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