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Sliding Stability of Cable-Assisted Tracked Equipment on Steep Slopes

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The increasing use of cable-assisted steep-slope harvesting has presented different operational, safety, and environmental opportunities and challenges. One of the primary benefits is the increased safety introduced when tethered equipment is used appropriately—notably, "appropriate" use is the use of cable tension for assistance, not stability. However, the stability of such equipment on realistic soils under wet or dry conditions is not well defined, blurring the transition between tethering as a safety measure or as an aid for traction. Therefore, we propose an approach that enables assessment of the stability and required tensions to ensure stable equipment operation under various configurations on steep slopes. A sensitivity analysis was performed, including two equipment track geometric parameters: track width and grouser depth, and soil properties by evaluating two distinctive soil types. Equipment geometry had a role in stability, but less than the influence of soil shear strength. For equipment properties, grouser depth presented the greatest effect on stability, concentrated between slopes of 36–70 percent. Greater soil moisture increases equipment stability in sandy loams and significantly decreases stability in clay loams. When the effects of soil properties are isolated, cohesion and angle of friction are the properties with the greatest effect on equipment stability.

Keywords: tethered, harvesting, forest, steep slope, stability

Feller-bunchers have been used on progressively steeper slopes for the past 30 years to improve worker productivity. However, with use on increasingly steep terrain, there are higher risks of unsafe operating conditions and potential negative soil impacts. For example, in Washington State (USA), the operation of feller-bunchers without cable assistance is permitted on slopes below 60 percent. However, building upon early feasibility studies of a self-contained cable "tethered" system carried out by the USDA Forest Service (McKenzie and Richardson 1978), there has been increased use of tethered technology for extending the range of slopes upon which mechanized equipment may operate. The technology, although experiencing an increased use in the United States, has been widely used worldwide. Tethered harvesters and forwarders have been available in Europe for at least 15 years, although it has been primarily limited to wheeled equipment (Bombosch et al. 2003, Visser and Stampfer 2015). Experiments with tethered feller-bunchers began in New Zealand in about 2008 (Amishev and Evanson 2010) and have rapidly expanded since then. Concurrent to this growing popularity have been challenges associated with steep terrain, including stability, traction, and anchoring (Stampfer 1999, Visser and Berkett 2015). Visser (2013) showed the effect of tether tension on extending the operating range for feller-bunchers for various traction coefficients. Visser and Stampfer (2015) suggested that overturning of untethered machinery on steep slopes is likely preceded by loss of traction that prompts sliding, followed by rapid downhill acceleration until an obstacle is encountered. Sessions et al. (2017) presented a theoretical model for both tethered and untethered feller-buncher overturning stability that considered use of a portion of soil strength limited by a specified maximum track slip. The analysis was limited to linearly elastic soils.

Our present work builds upon the prior study by better capturing the sliding stability of equipment considering realistic soil properties in the context of current safety considerations. In particular, an important yet nebulous safety criterion that has been considered for steep-slope operation is that the equipment could

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sit on the slope, untethered, without sliding. In this paper, we present a model for sliding for rigid track equipment on steep slopes. This consideration is important not only for safe operation, but also potentially for soil disturbance. We define three cases that limit tethered equipment mobility on steep slopes:

1. Mobility in the uphill travel direction limited by excessive track slip; i.e., track speed is greater than translational speed.
2. Mobility in the downhill travel direction limited by excessive track skid; i.e., translational speed is greater than track speed.
3. Sliding where equipment is moving downhill and tracks are not turning.

Sessions et al. (2017) analyzed cases 1 and 2 for a linearly elastic soil for a tracked carrier with a rigid suspension for linearly elastic soils. In this paper, we focus on case 3, sliding, and consider both linearly elastic and nonlinearly elastic soils while also accounting for realistic soil properties under both wet and dry conditions. In order to establish the effect of equipment track geometry and soil properties on sliding stability, a sensitivity analysis with an example is presented.

Methodology

To assess the sliding stability of the tracked equipment, an approach based on static force equilibrium is developed. First, equations of equilibrium relating soil shear strength to a factor of safety (FS) against sliding are developed. Thereafter, we develop equations of moment equilibrium to determine the effective length of track in contact with the ground. Finally, we evaluate the influence of track geometry and soil properties on sliding stability and illustrate these influences with an example.

Factor of Safety and Tether Tension

Sliding stability is evaluated by assessing equilibrium of forces, both parallel and perpendicular to the surface of the slope. By treating the combined weight of the equipment components as W, on a slope θ, assisted by a cable force in line with the slope, P, equilibrium parallel and perpendicular to the tracks may be evaluated as:

$$\sum F_{\parallel} = 0 = T + P - W \sin\theta \tag{1}$$

$$\sum F_{\perp} = 0 = N - W \cos\theta \tag{2}$$

where mobilized shear force, T, along the representative track length is defined as:

$$T = W \sin\theta - P \tag{3}$$

and normal force along the tracks, N, as:

$$N = W \cos\theta \tag{4}$$

Assuming Mohr–Coulomb soil properties, the soil shear resistance (Jumikis 1987), S, is:

$$S = c' + \sigma' \tan\phi' \tag{5}$$

Where ϕ' is the effective internal angle of friction ranging from 0° to 45° (ranging between undrained loading of clay and angular gravel, respectively), c' is the effective cohesion ranging from 0 to 1,000 kPa (ranging between sand/gravel and over consolidated clay, respectively), and the effective normal stress, σ', is defined as:

$$\sigma' = \frac{N}{2\,(\mathrm{TW})\,(\mathrm{LE})} = \frac{W\cos\theta}{2(\mathrm{TW})(\mathrm{LE})} \tag{6}$$

where LE is the effective length of track in contact with the ground surface, and TW is the width of each track; these are multiplied by 2 to represent two tracks. Substituting Equation 6 into Equation 5 yields:

$$S = c' + \frac{W\cos\theta}{2\,(\mathrm{TW})\,(\mathrm{LE})}\tan\phi' \tag{7}$$

The required shear stress (τ) is defined by dividing Equation 3 by the effective track length, LE and 2 × TW, defined as:

$$\tau = \frac{T}{2\,(\mathrm{TW})\,(\mathrm{LE})} = \frac{W\sin\theta - P}{2\,(\mathrm{TW})\,(\mathrm{LE})} \tag{8}$$

Finally, an FS for sliding can be defined by taking the ratio of available shear strength (Equation 7) against the mobilized shear stress (Equation 8), as shown:

$$\mathrm{FS} = \frac{S}{\tau} = \frac{c' + \dfrac{W\cos\theta}{2\,(\mathrm{TW})\,(\mathrm{LE})}\tan\phi'}{\dfrac{W\sin\theta - P}{2\,(\mathrm{TW})\,(\mathrm{LE})}} = \frac{2c'\,(\mathrm{TW})\,(\mathrm{LE}) + W\cos\theta\tan\phi'}{W\sin\theta - P} \tag{9}$$

This equation can be used to determine the relative stability against sliding for cable-assisted equipment or modified to solve for the required cable tension by setting the FS to a predetermined number and solving for the cable force, P. For example, by setting FS to unity, the required cable tension is:

$$P = W\sin\theta - 2c'\,(\mathrm{TW})\,(\mathrm{LE}) - W\cos\theta\tan\phi' \tag{10}$$

To determine the effective track length, a moment equilibrium approach is outlined below (Figure 1).

Effective Track Length in Contact with Soil

Bekker (1956) proposed that pressure and sinkage could be expressed as:

Management and Policy Implications

The use of cable-assisted harvesting and logging equipment has grown exponentially in the Western United States and Canada. These systems have been available and operating in other countries with active logging in steep-slope terrain for at least a decade, including European counties, New Zealand, and Chile among others. Each country presents different challenges for operating this equipment, including differences in soil, climate conditions, and policy, especially concerning safety and environmental regulation. This study complements efforts from research and industry focusing on specific limitations for this technology in areas where timber was historically harvested with different approaches because of safety and operational challenges. State agencies in the Western United States are currently considering regulations for these specific systems in terms of safety and potential soil and water impacts. We believe our study contributes to a better understanding of safety issues regarding the safe operation of tethered equipment, while also mitigating some forms of potential soil disturbance.

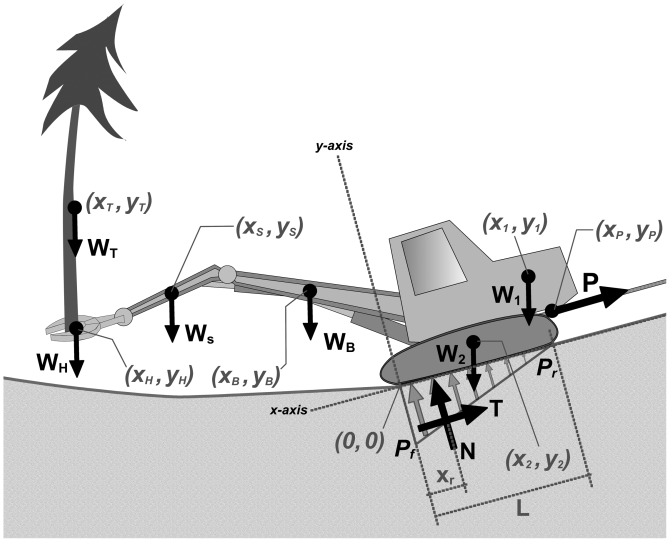

Figure 1. Free body diagram, dimensions and nomenclature used in force and moment equilibrium analyses (from Sessions et al. 2017).

$$p = \left(\frac{k_c}{\mathrm{TW}} + k_{\mathrm{phi}}\right) z^n = k\, z^n \tag{11}$$

where p is the normal pressure, z is sinkage, k_c, k_{phi}, and n are empirical soil properties representative of the elastic soil response, and TW is the width of the track. The value of the exponent n can usually range between 0.2 and 1.7. We assume on steep slopes that the upslope-facing end of the track will be unloaded. Since, for a rigid track, the sinkage represented by $z(x)$ along the track is linearly related to distance along the track, the sinkage at distance x along the loaded track length is defined as:

$$z\,(x) = z_o - z_o\left(\frac{x}{\mathrm{LE}}\right) \tag{12}$$

where z_o is the maximum sinkage, and LE is the effective length of the track in contact with the ground. The resultant of the pressure distribution, N, under both tracks is then defined as:

$$N = 2\ \mathrm{TW}\int_0^{\mathrm{LE}} p(x)\mathrm{d}x \tag{13}$$

and consequently, the sum of the moments about the front edge of the tracks is:

$$N\ X_r = 2\ \mathrm{TW}\int_0^{\mathrm{LE}} p\,(x)\ \ x\ \mathrm{d}x \tag{14}$$

Substituting Equations 11 and 12 into Equations 13 and 14, integrating, and simplifying yields an effective track length defined as:

$$\mathrm{LE} = X_r(n+2) \tag{15}$$

From Equation 15, when $n = 1$, then $X_r = \mathrm{LE}/3$—an expected result for a linear pressure distribution (i.e., triangular) under a rigid suspension when LE is less than the track length. As n goes to 0, X_r approaches LE/2, realizing a resultant that moves upslope. When $n > 1$, X_r moves toward the downhill edge of the track. If LE from Equation 15 is greater than the track length, then LE is equal to the track length. This limiting scenario implies that the entire track is in contact with the slope.

To calculate X_r, and thus LE, we use the nomenclature from Sessions et al. (2017)—see Figure 1. The resultant normal reaction force acting underneath the tracks, R, can be calculated by summing the normal forces on tracks. Once X_r is calculated, LE can be determined, and hence the FS (Equation 9) or tether tension (Equation 10) for a given sliding scenario may be assessed. However, this derivation does not yet take into account the influence of track grousers, which may directly contribute to stability. Grousers increase the forces that resist sliding with two general mechanisms. The first is that the grouser height, h_g, increases the shear area along the sides of the track, in turn increasing the forces resisting equipment sliding. This added contribution can be expressed in terms of the grouser height-to-track-width ratio, h_g/TW (Bekker 1956). Alternatively, the grouser height enables mobilization of passive resistance of soil in front of the tracks, P_p (Bekker 1956). To incorporate these influences, Equations 9 and 10 may be modified for the effects of grouser height, h_g and flow value, K_p to become:

$$\mathrm{FS} = \frac{S}{\tau} = \frac{ac'2(\mathrm{TW})\mathrm{LE} + bW\cos\theta\tan\phi' + 2P_p}{W\sin\theta - P} \tag{16}$$

where

$$P_p = \frac{1}{2}\gamma h_g^2(\mathrm{TW})K_p + 2c'(\mathrm{TW})h_g\sqrt{K_p} \tag{17}$$

and the influence of the grouser height to track width is defined using factors a and b, defined as:

$$a = 1 + 2\left(\frac{h_g}{\mathrm{TW}}\right) \tag{18}$$

$$b = 1 + 0.64\left(\frac{h_g}{\mathrm{TW}}\right)\cot^{-1}\left(\frac{h_g}{\mathrm{TW}}\right) \tag{19}$$

The influence of grouser resistance, from both passive pressure and grouser depth, can in turn be introduced by rearranging Equation 17 to be a modified version of Equation 10, defining cable tension as:

$$P = W\sin\theta - ac'2(\mathrm{TW})\mathrm{LE} - bW\cos\theta\tan\phi' - 2P_p \tag{20}$$

Since the effective track length influences the needed tether tension for sliding stability, Equation 15 may be introduced into Equation 20 to yield:

$$P = \frac{W\sin\theta - \dfrac{ac'2(TW)\,(n+2)}{N}\left[(W_1X_1 + W_2X_2)\cos\theta - \mathrm{SumOver}_1 - \mathrm{SumOver}_2\right] - bW\cos\theta\tan\phi' - 2P_p}{1 + \dfrac{ac'2(\mathrm{TW})(n+2)y_p}{N}} \tag{21}$$

This definition enables direct assessment of the influence of grousers, track width, slope, soil conditions, equipment dimensions, and configuration on either sliding stability or required tether tension.

Sensitivity Analysis

A series of sensitivity studies were performed to assess the relative influence of various equipment configurations and soil conditions on realized tether tensions required to remain stable against sliding. For comparative purposes, a baseline set of equipment dimensions based on Sessions et al. (2017), a nonleveling cab harvester, and soil conditions were selected, presented in Table 1. The sensitivity studies include an evaluation of grouser depth, track width, soil strength, and soil stiffness, based on empirical soil parameters by Wong (2008) shown in Table 2. Each scenario was evaluated when the boom is facing uphill or downhill. The baseline grouser height was 5.08 cm and was compared with grouser heights 10.2 cm and 15.2 cm (G1 and G2 conditions). The baseline track width was 61 cm with comparative examples of 66 cm and 76 cm. For soil, the baseline conditions were $c' = 14$ kPa, $\phi' = 15°$ and $n = 0.5$. These parameters were changed to compare two contrasting soil types, a clay loam and a sandy loam under wet (*CW* and *SW*) and dry conditions (*CD* and *SD*). A comprehensive table outlining sensitivity analyses is shown in Table 2.

Results

Influence of Grouser Height

As expected, increasing grouser height decreases the tether cable tension, consequently making the equipment stable at greater slopes by the added shear resistance. For example, when the grouser length is increased by 5 cm, there is an approximately 19 percent decrease in tether tension on slopes of 31° (60 percent) and 6 percent decrease in slopes greater than 39° (80 percent) (Figure 2A). Likewise, the decrease in tension is approximately 15 percent for slopes greater than 39° when grouser depth is increased by 10 cm. This effect is amplified when the boom is facing uphill because the center of mass of the equipment is opposite to the direction of sliding and results in a more favorable distribution of effective track contact area with the underlying soil (Figure 2B).

Influence of Track Width

Feller-bunchers may be manufactured with different track systems, including different track widths, which influences sliding stability on slopes. Increasing track width increases stability by increasing the effective track area that mobilizes shear resistance *and* by increasing passive resistance in front of the tracks. That is, an increase in TW results in a larger passive wedge at the downslope end of the tracks, increasing P_p. The effective area of the tracks that is in contact with the soil also contributes to shear resistance through added mobilization of cohesive shear strength, a direct function of contact area, as demonstrated in Equation 20. Both of these components reduce the tether tension required for stability. However, the influence of a wider track length is less pronounced than the effects of deeper grousers. The width of the tracks contributes to shear and passive resistance of the tracks, but is largely still governed by the eccentricity of the equipment. In eccentric cases, the effective length of the tracks is rather small; hence the increase in area from wider tracks is muted. Nonetheless, increasing the track width from 61 cm to 66 cm results in a decreased tension required for sliding stability of about 2–3 percent, even less at steeper slopes (e.g., greater than 35° [70 percent], Figure 3A). The effects of widening a track are more pronounced when the boom is facing uphill, and the track contact length is greater than the downhill case (Figure 3B).

Influence of Soil Properties

Resistance to sliding increases in soils with greater shear strength, characterized as magnitudes of soil cohesion and soil angle of internal friction. When a soil has higher levels of cohesion, the equipment can remain stable at steeper slopes. This level of stability is particularly pronounced when the equipment is less eccentric, and more of the track is in contact with the soil. Increased friction angles directly contribute to stability, but tend to be more independent of effective track length as the resistance is directly related to track pressure. In addition, the soil sinkage exponent n in Equation 11 demonstrates some dependency on the type of soil. This empirical property is conventionally assumed to be 0.5 for "average" conditions (Bekker 1956), but its quantity spans an order of magnitude. Despite this range, the observed results do not show extreme sensitivity to the exponent. Wong (2008) shows exponents ranging from 0.11 (40 percent moisture content heavy clay) to 1.1 for dry sand. A larger n value results in less sinkage.

The moisture conditions of a given soil may greatly influence stability. For equipment with a boom-downhill orientation, a sandy loam soil under dry conditions may sustain equipment stability on slopes below 31° (60 percent). The same soil would require 6,000 kgf of cable tension to remain stable at a 40° (84 percent) slope, but might require negligible cable tension for stability when moisture is present in the soil. This may be attributed to apparent cohesion that stems from increased suction in sandy materials that are subject to partial saturation. In the case of a wet clay loam, less mobilization of friction results in increased cable

Table 1. Baseline equipment component weights and soil properties.

Equipment specifications		
Weight of cutting head	W_h (kg)	2,608
Weight of stick	W_s (kg)	2,268
Weight of boom	W_b (kg)	3,629
Weight of the undercarriage	W_1 (kg)	12,700
Weight of the upper system	W_2 (kg)	14,515
Equipment weight	W (kg)	35,720
Grouser height	h_g (cm)	5.1
Track width	TW (cm)	61
Soil properties		
Soil cohesion	c' (kPa)	14
Angle of friction	ϕ' (°)	15
Spring soil constant	n	0.5
Unit weight of soil	γ (kN/m^3)	12
Passive earth pressure coefficient	K_p	1.70

Table 2. Summary of sensitivity analysis.

		Base	G1	G2	T1	T2	CW	CD	SW	SD
Equipment specifications										
Grouser height	h_g (cm)	5.1	10.2	15.2	5.1	5.1	5.1	5.1	5.1	5.1
Track width	TW (cm)	61	61	61	66	76	61	61	61	61
Soil properties										
Soil cohesion	c' (kPa)	14	14	14	14	14	20.7	69	1.38	1.72
Angle of friction	φ' (°)	15	15	15	15	15	6	34	38	29
Spring soil constant	n	0.5	0.5	0.5	0.5	0.5	0.11	0.13	0.2	0.7

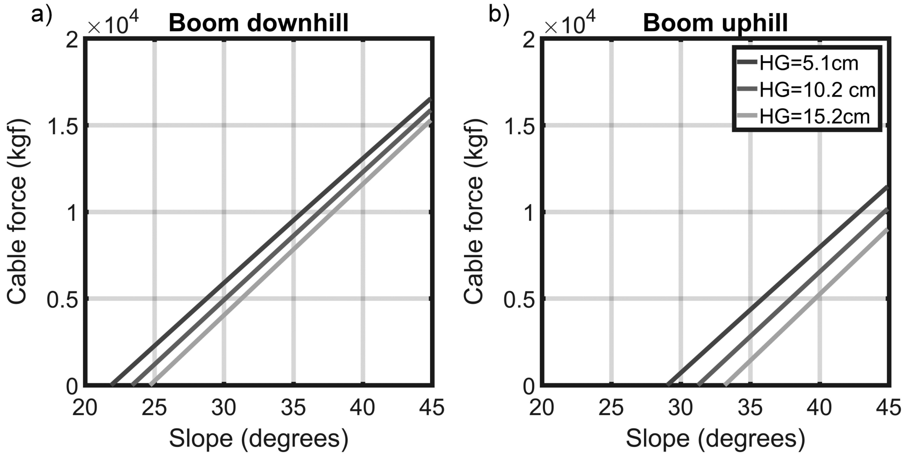

Figure 2. Cable tension at different ground slopes for equipment with different grouser height (scenarios: base, G1 and G2): (a) boom downhill and (b) boom uphill.

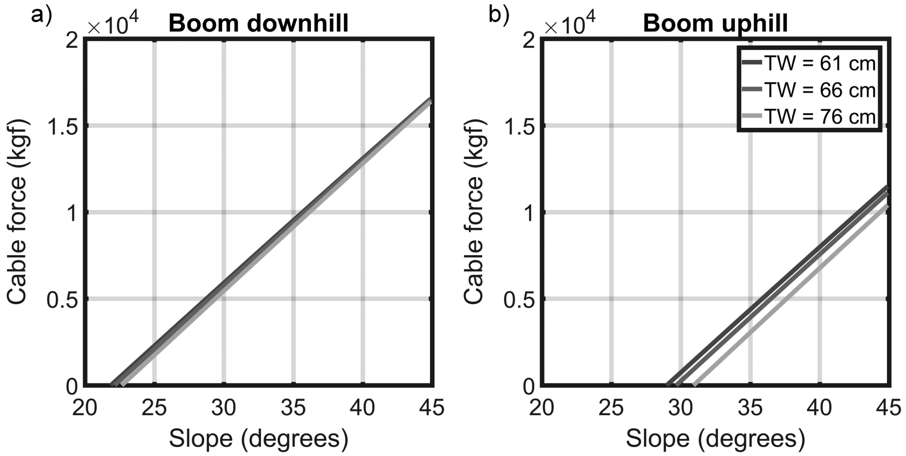

Figure 3. Cable tension at different ground slopes for equipment with different track width (scenarios: base, T1 and T2): (a) boom downhill and (b) boom uphill.

tensions needed to keep the equipment stable. For example, even on slopes less than 20° (36 percent), the tension required for that slope is estimated to be 3,000 kgf. Equipment operating on dry clay loam presents a different scenario—even greater stability than wet sandy loam is realized because of a greater angle of friction and significant apparent cohesion stemming from significant suction and capillary action in the partially saturated, fine-grained soil matrix. For example, at a 40° slope, on a downhill boom position, the cable tension increases by 16,000 kgf when on a saturated clay soil versus the same soil under dry conditions (Figure 4A).

The configuration of equipment may greatly influence resistance to sliding, primarily displaying sensitivity to mobilization of cohesion along effective track length. When the boom is uphill, the cable is only needed for stability on slopes over 25° (47 percent) when placed on wet clay loam. In the case of sandy loam soil, the changes in tether tension are very similar compared with the downhill boom position. In this case, the equipment stability is governed by frictional strength, which is less dependent on the length of track that is engaged in the underlying soil (Figure 4B).

The maximum slope that may sustain equipment stability without cable assistance is presented in Figure 5 for a range of potential soil properties. For example, an increase in the angle of friction from 15 to 30° increases the maximum stable slope from 21 to 33° (38–65 percent) when the boom is downhill, a relatively linear trend. On the other hand, an increase in cohesion from 20 to 40 kPa increases the stable slope by 4° and from 40 to 60 kPa by only 2°, the relation is shown to be a positive nonlinear relation, primarily exhibiting the largest influence on stability when the boom is facing uphill. This is due to enhanced mobilization of cohesive resistance with increased effective LE during uphill operation. Cohesion tends to have a greater effect on equipment stability between 5 and 60 kPa (Figure 5C).

Discussion

The presented sensitivity studies demonstrate that soil properties may exhibit more influence than equipment configuration or add-ons, such as deeper grousers or wider tracks. Soil properties are highly variable between and even within a given site (Garten et al. 2007), a complexity that makes generalization of results difficult. However, the presented analysis does demonstrate the relative influence of several important geotechnical soil properties on equipment stability and, in turn, stability and tether tension requirements.

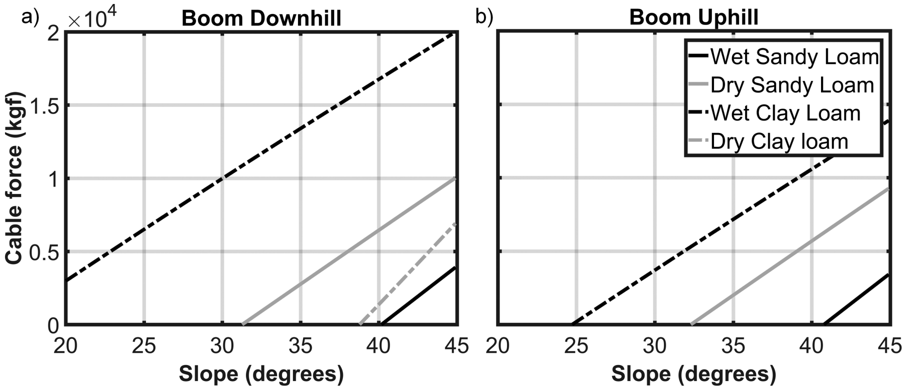

Figure 4. Cable tension at different ground slopes for different soils in dry and saturated conditions: (a) boom downhill and (b) boom uphill.

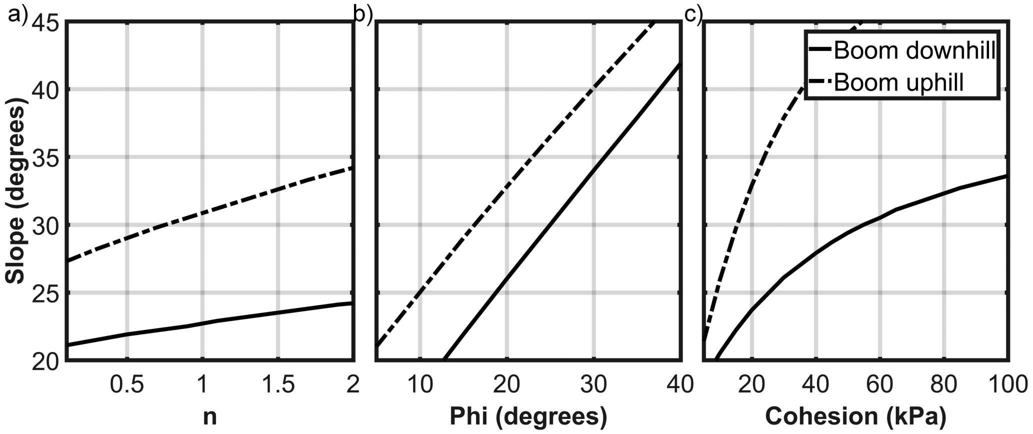

Figure 5. Maximum stable slope for base soil at different: (a) soil exponents, (b) friction angles, and (c) cohesions.

For example, sandy loam demonstrated stability on steeper slopes than clay loam under moist conditions, primarily because moisture can actually increase the apparent cohesion of sandy soils through increased capillarity. The same may apply to clays, but the added moisture may actually decrease the effective strength of clay as it undergoes undrained loading—specifically, a buildup of pore water pressure that restricts the mobilization of shear strength under the rapid loading of equipment operation under wet conditions. These soil conditions are not constant over time; that is, they may exhibit very different behaviors between wet and dry conditions, directly affecting the effective shear strength properties realized under equipment loading. This observation, although intuitive, is illustrated quantitatively—for example, the selected clay loam could accommodate slopes up to 80 percent under dry conditions, but was limited to less than 35 percent under wet conditions when the boom is downhill. From the selected study, less cohesive soils such as sandy loam are less sensitive to moisture, but exhibit greater stability under moist conditions. The importance of cable assistance is highlighted here, as stability cannot be sustained under untethered conditions on slopes greater than 31° under dry conditions. Soil moisture has a significant influence on the realized mechanical properties of soil, especially cohesion (Mouazen et al. 2002). For this reason, a planner needs to understand site-specific soil properties and how they change under the environmental conditions under which operation will occur.

The presented calculations incorporated nonlinear sinkage, an important consideration in context of track interaction, particularly in cohesive soils where effective track length directly affects stability. This nonlinearity is captured in scenarios where the soil exponent n is a value other than unity. For the case of a soil exponent, the model simplifies to linear sinkage conditions. The soil exponent is an empirical number and depends strongly on the soil moisture content, and sinkage of the equipment. However, compared with other soil properties, it does not have a large impact on equipment stability. This observation suggests that models assuming linear relations between sinkage and pressure are likely adequate, but sufficient characterization of soil shear strength under wet and dry conditions is critical. Further research is needed to include sinkage as an addition to undulating terrain and alternative equipment mounting (i.e., wheeled equipment). Yet, this study still provides quantitative insight into the effective influence of this behavior.

Despite the governing influence of soil conditions, grouser depth could significantly affect the realized stability of equipment. Stability increases with grouser height as it mobilizes more soil shear resistance, from both the formation of passive pressure and the relative depth of the grousers compared with the track width (i.e., side resistance). However, this influence was attenuated at steeper slopes and may have some practical constraints, namely uneven terrain, the presence of shallow rocks, soil buildup under the tracks, and

Figure 6. Top: shear plane resulting from sliding of an untethered harvester on wet clay soils. Bottom: stabilized machine after sliding was arrested.

logging residue or slash. The presence of such material may constrain the tracks from mobilizing full soil shear strength for traction. The inability to be stable in these conditions could increase soil displacement, a form of soil disturbance. However, slash mats may also provide a benefit as they reduce direct contact of tracks with mineral soil and in turn redistribute pressure in a more advantageous manner to the underlying soil.

Model Comparison with Field Data

The proposed model is compared with an actual sliding failure that was observed for an unleveled, untethered harvester located on a 21° (38 percent) slope composed of wet clay. As shown in Figure 6, the machine sheared the underlying wet clay in translation on a relatively gentle slope, defined as a sliding failure. The machine was facing downslope and had the same dimensions as presented in Table 1 with the exception of the boom, stick, and head, which had centers of gravity of –101 cm, –178 cm, and –203 cm, respectively. No tree was being handled during failure. After failure, the undrained shear strength (c_u) of the soil within the shear plane was measured to be approximately 20 kPa using a vane shear device (ASTM D5273). The soil was classified as high-plasticity clay using the Unified Soil Classification System per ASTM D2487 guidelines. As the conditions were wet and the native soil fine-grained, undrained shear strength (c_u) was assumed to govern, meaning that no friction (ϕ') was mobilized within the underlying soil. Using the proposed approach and described site parameters, the slope where tether tension was required for stability was 22° (40 percent). Thus, for the given soil and equipment parameters, the untethered machine was unstable and slid accordingly, in agreement with field measurements and observations. Varying the measured undrained shear strength by ±10 percent yields maximum untethered slopes of 21° (38 percent) and 23° (43 percent), respectively. It should be noted that the equipment was unstable on a relatively gentle slope in this scenario, operating within typical grades for untethered equipment. Owing to the relatively low undrained shear strength of the normally consolidated, wet highly plastic clays on site made the machine unstable. For the measured values, a cable tension of only 6000 kgf would have enabled safe operation at up to a 30° (57 percent) slope.

Conclusions

This paper presents a deterministic approach toward assessing sliding stability and required cable tension for tethered feller-bunchers on steep slopes. This approach accounts for equipment geometry, configuration, and soil conditions. The major conclusions are as follows:

- Equipment track geometry can have an effect on sliding stability, grouser height being the one with the greater effect of the two analyzed scenarios. Tether tension decreases by a greater amount at less pronounced slopes, and the effect decreases as slope increases.
- Soil properties generally govern equipment stability when compared with equipment geometry. Stability is directly dependent on soil moisture; higher moistures in clayey soils may reduce stability, whereas the opposite may be true in sandier soils. Consideration of the influence of these properties is important, especially when considering safe operation, appropriate use of cable assistance, and decreased soil disturbance.
- The influence of soil shear strength, namely cohesion and angle of friction, directly affects equipment stability. Stability has a linearly positive relation with angle of friction and a positive nonlinear relation with cohesion.
- A short case study in the field illustrates that under wet conditions, untethered equipment may fail on relatively gentle slopes. However, this adverse scenario may be avoided through the use of cable assistance.

Future work could improve on this approach by taking into account the influence of equipment when asymmetrically oriented on a slope (e.g., adversely placed on a cross-slope), account for cable not being in line the equipment direction, leveling cab equipment, account for uneven terrain and hummocks, and better assess dynamic conditions during movement. However, this framework provides a logical approach toward assessing the sliding stability of tethered machinery on steep slopes, a condition that is critical for safe operation of "cable-assisted" equipment.

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