Original scientific paper

Designing Mobile Anchors to Yield: A Tension Relief System for Tail Anchoring

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Abstract

Cable yarding systems are a common method for transporting materials in mountainous terrain where environmental, safety or economic considerations do not permit ground-based methods such as skidding, forwarding or shovel-logging. Although effective in steep terrain, cable yarding requires anchored support for skyline and operating line operation. Furthermore, mechanized steep slope harvesting, which often uses cable assistance, also necessitates sufficient anchoring for large cable loads. These systems rely on a fixed anchor, or tailhold, to provide adequate line restraint for operation. Anchored guylines and skylines usually depend on available stumps or trees (Peters and Biller 1985). Where these are not available, mobile anchors such as bulldozers or excavators can be used. Mobile equipment anchors have an advantage of predictable resisting capacity, as opposed to trees and stumps, and may present a means of relieving excessive cable tensions in skyline systems without a catastrophic failure. We present a design approach for skyline tension relief with a comparison to actual field data. The analysis demonstrates that exceedance of a mobile anchor sliding resistance results in movement, limiting maximum skyline tensions and subsequently reducing them after the anchor shifts forward. Other anchor types, like stumps, anchored deadmen and engineered anchors, do not have the tendency for gradual movement to relieve skyline tensions as failure is often catastrophic, resulting in higher and potentially dangerous cable tensions, and complete loss of cable tension at failure. For mobile anchors, a relationship between cable tension and length presents an efficient means of predicting the anchor movement to facilitate design of appropriate equipment setback. A comparison of an analytical approach based on cable tensions, cable lengths, and anchor capacity with instrumented field tests demonstrates that the use of equipment, as a primary or auxiliary anchoring system, can be effective and potentially safer when adhering to design constraints based on equipment, equipment placement and in-situ soil properties.

Keywords: cable logging, artificial anchors, failure capacity, movement, design, skylines, mobile anchors, dynamic loading

1. Introduction

Cable logging systems require anchored support(s) to maintain safe and effective yarding of materials in steep terrain. This support can come from a variety of techniques including buried deadman anchors, stumps or trees, rock anchors or heavy equipment (also known as a mobile anchor, machine anchor or equipment anchor). These anchoring types are often used for guylines to support yarding towers, end support (tailhold) for skylines under loading and high tensions or cable-assisted mechanized harvesting equipment. The most common method for tail support is attachment to nearby, adequately sized trees or stumps (Pyles et al. 1991, Smith 1995) – a resource that can be a challenge with increasingly shorter stand rotations and the smaller available trees, younger or smaller adjacent stands, and property boundaries. Designing with stump anchors typically involves consideration of tree diameter and species (Pyles et al. 1991, Smith 1995, Peltola et al. 2000), but tends to have a highly variable load capacity that is difficult to define, and their application is often dependent on the subjective judgment of workers installing a logging system. Alternatively, engineered anchors, such as buried deadmen, augered anchors, plate anchors and mobile anchors may present less variability in capacity and can account for specific soil conditions (Copstead and Studier 1990, Hartsough et al. 1997). However, fixed anchors like buried deadmen, augered anchors, or plate anchors are subject to catastrophic failure (pullout, rupture, breakage) when their capacity is exceeded, and can result in significant, potentially unsafe cable tensions if of sufficient capacity. When capacity is exceeded, anchor failures can have catastrophic results. Oregon has had at least four fatalities in the past decade from insufficient anchoring, including one fatality from a failed mobile anchor in 2006 (OR-FACE 2016). One method of preventing overloaded skylines is to have tension limiting slipping brakes on the skyline, but this alone will not protect against skyline anchors of unknown capacity. In this study, the focus is on mobile anchors, i.e. equipment anchors, and their capability to avoid catastrophic failure and excessive cable tensions under optimal design conditions.

Mobile anchors often use heavy construction or logging equipment as a dead weight that can resist cable tensions during yarding. Typically, this equipment consists of excavators, bulldozers, skidders, and other heavy machinery (see Fig. 1). Soil berms, hillslopes, or embedded equipment shovels or blades can be used for extra resistance when necessary. The soil in front of the equipment can provide added anchor capacity by means of soil self-weight and passive shear resistance based on soil cohesion and angle of internal friction, in turn providing more resistance (Oregon OSHA 2008, Leshchinsky et al. 2015). Embedding the mobile anchor, although increasing the potential for equipment overturning, does allow added passive soil resistance.

Mobile anchors present advantages in a variety of scenarios where cable resistance is required. Where alternative anchoring methods are inadequate, mobile anchors present a means of providing resistance to cable loads, especially for skylines or cable-assisted harvesting equipment, which incur high tensions (Visser and Stampfer 2015, Visser and Berkett 2015, Leshchinsky et al. 2015, Olund 2001). For example, when stump anchors are used as tail support, anchor failure will often involve complete pullout of the stump, and potentially, a rapid subsequent succession of failures of other stump anchors in the system. This can result in a swift loss of tension in the skyline, potentially endangering workers near the skyline or carriage. Furthermore, anchoring plays a critical role in mechanized harvest on steep slopes, particularly in Europe and New Zealand, where cable-assisted feller-bunchers or harvesters rely on mobile anchoring to ensure that cable assistance is stable and sufficient (Visser and Stampfer 2015, Visser and Berkett 2015, Stampfer 1999). If anchoring is sufficiently strong, excessive cable loads can develop during yarding, resulting in cable tensions that may seriously overtension the skyline or guylines that could destabilize the yarding tower or bring a cable to rupture.

Fig. 1 Bulldozer using a mobile anchor

Cable tension is a function of cable geometry and the applied forces to the cable system, including self-weight of the cable. For a given external loading and horizontal distance between supports, the greater the sag in the skyline between supports, the more efficient the skyline is at providing vertical carrying capacity per unit of horizontal force. If a mobile anchor moves forward, the sag in skyline increases the vertical/horizontal force efficiency reducing the skyline tension. Mathematical models for skyline yarding have been embedded in a number of software including the publically available Skyline XL software (USFS 2015).

The reduced tensions resulting from increasing the line length between supports coupled with a mobile anchor tendency to move forward under increasing tension presents a unique opportunity to prevent catastrophic anchor or skyline failures, as well as tipping of yarding towers. For a given payload, cable sizing and length, it is well known that an increase in line length between fixed ends results in significantly reduced cable tensions (Kendrick and Sessions 1991, Brown and Sessions 1996). Concurrently, an increase in cable tensions results in increased mobilization of mobile anchor resistance, ultimately resulting in yielding soil located at both the equipment suspension (treads, tires, grousers, etc.) and embedment zone (berms, embedded blades, etc.). When designed appropriately, these regions of frictional resistance yield, enabling sliding of the vehicle and a rapid decrease in skyline tensions while maintaining cable suspension and yarder stability. After soil yield and movement, the equipment can simply be moved back into place under its own operating power. Thus, such a system may present a safety relief system to prevent catastrophic failures of anchors, cable rupture and yarder tip-overs in an economically feasible way.

For safety, the design failure mode must be sliding rather than equipment rollover. That is, the skyline must be attached to a point on the equipment that is relatively low to the ground (frequently to the drawbar or a winch), the equipment center of gravity must be set back a sufficient distance from point of rotation, and/or the passive resistance from embedment must be sufficiently small. Such a requirement can be challenging for bulldozers, which have a center of gravity that is not located far from anchor attachment point. A low anchor attachment point, which is often a drawbar or an axle (Oregon OSHA 2008) may counteract large overturning moments, enabling equipment sliding to the governing mode of yielding. The center of gravity is a factor specific to the equipment chosen to serve as a mobile anchor. Furthermore, if sliding is to govern, it is critical that a sufficient distance is chosen between the equipment location and any potential precipices, like steep downslopes or cliffs.

In this study, a formulation is presented coupling skyline tension behavior with yield of mobile anchors based on an analytical solution. The theorized relationship between equipment movement from soil yield and reduced skyline tensions are validated with data from an instrumented field test involving an equipment anchor serving as a tailhold.

2. Analytical design

The design involves a calculation of mobile anchor capacity based on prior research (Leshchinsky et al. 2015), specifically for sliding. A comparison of anchor capacity and skyline tensions from a field test are compared. A curve of cable tensions was generated from the publically available payload analysis program, Skyline XL (USFS 2015) for a variety of yarding distances to represent the reduction of cable tension with equipment movement from sliding. Based on the coupled relationship of the loading curve and anchor sliding capacity, a design approach is presented to reduce risk of catastrophic yarder, skyline, or anchoring failure by means of mobile anchor yield.

2.1 Anchor capacity

A static force equilibrium analysis is used to determine anchor capacity for an array of scenarios described by slope gradient, cable angle, equipment weight, soil strength, equipment embedment depth, blade width and track interaction parameters (Leshchinsky et al. 2015).

$$F=\frac{(\frac{1}{2}\gamma D_{\mathrm{b}}^{2}w_{\mathrm{b}}K_{\mathrm{p}}+2cw_{\mathrm{b}}\sqrt{K_{\mathrm{p}}})\left(\sin\beta+\cos\beta\frac{\cos\beta-\tan\delta_{\mathrm{t}}\sin\beta}{\sin\beta+\tan\delta_{\mathrm{t}}\cos\beta}\right)+cA_{\mathrm{t}}\left(\sin\beta+\cos\beta\frac{\cos\beta-\tan\delta_{\mathrm{t}}\sin\beta}{\sin\beta+\tan\delta_{\mathrm{t}}\cos\beta}\right)+W_{\mathrm{t}}}{\left(\sin\theta+\cos\theta\frac{\cos\beta-\tan\delta_{\mathrm{t}}\sin\beta}{\sin\beta+\tan\delta_{\mathrm{t}}\cos\beta}\right)} \tag{1}$$

Where:

F	ultimate anchor capacity at failure
K_{p}	rankine passive earth pressure coefficient = tan (45°+ ϕ'/2)
ϕ	soil internal angle of friction
c	soil cohesion
δ_{t}	interaction between soil and vehicle support (tracks, tires, etc.)
β	angle of hillslope supporting equipment
θ	angle of skyline pull
D_{b}	depth of blade below ground surface
w_{b}	width of blade
A_{t}	tracked footprint
γ	unit weight of soil
W_{t}	weight of equipment

With wheeled equipment, the track area can be defined as zero. The weight of the equipment, W_t, is assumed to maintain full interaction (ϕ=δ) with the ground surface due to the aggressive treads (grousers) common to tracked equipment. The soil within and beneath the treads is assumed to shear together. Uneven loading and contact of

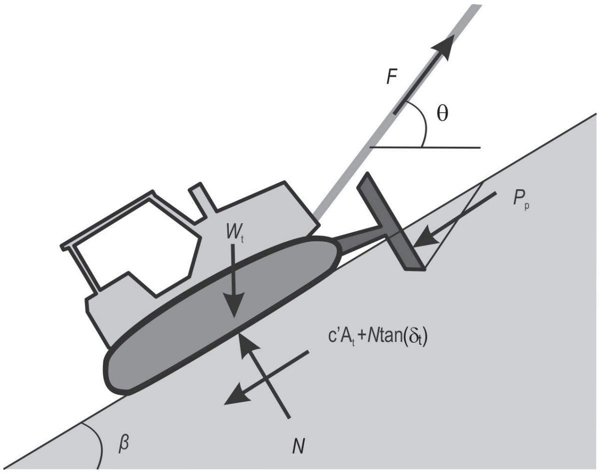

Fig. 2 Free-body diagram of mobile anchor system

the tracks with ground, called eccentricity, occurs due to large moments that can lift part of the equipment off of the ground. Loss of full ground contact can occur when the moment placed on the equipment due to the load becomes large. To mobilize any resistance due to equipment self-weight or traction, the brakes must be engaged.

2.2 Movement and clearance distance design

The presented anchor capacity equation presents a means of establishing a cable resistance that represents the point at which the soil supporting anchoring equipment fails in shear, allowing sliding and movement in the direction of pull and a relief in skyline tension. This point of yield and associated ability to slide enables cable tensions to subsequently drop after a peak loading exceeds the soil resisting capacity, a phenomenon that occurs due to the direct, exponential relationship between skyline tension and cable yarding distance. That is, the decrease of the distance between the two points where a cable is fixed (e.g. a yarding tower and a tailhold) increases the cable sag, consequently reducing cable skyline tension with movement of the mobile anchor in the direction of pull. For a given configuration or corridor for yarding, a relationship cable tension and stretched length (anchor movement) can be calculated with associated cable tensions under loaded conditions (Kendrick and Sessions 1991). The maximum tension for any configuration can be found and adjusted to accommodate incremental movement of a tailhold towards the direction of pull, creating a load-cable characteristic curve (Fig. 3). The load-cable characteristic curve (LCCC) represents the reduction in maximum cable tension for a given yarding configuration for a range of potential yarding lengths, including those if a vehicle were to slide forward. These values could be generated using static equilibrium equations or publicly available software (e.g. Skyline XL, USFS 2015) and should be done for any specific situation (e.g. multi-span cable lines). The curve representing the change in skyline tension follows a general exponential decay function of the form:

$$Y = AX^{B} \tag{2}$$

This exponential function can be represented by a given load factor (A), representative of a load that is diminished with movement, multiplied by a site constant (S, dependent on site geometry, like angle at which a tailhold moves if shifted towards the direction of pull), to an exponent that is the horizontal movement of the tail point towards the direction of pull (ΔL). The simple exponential function representative of the LCCC is defined in equation (3) as:

$$F = \mathit{Load\ factor} \cdot \mathit{Site\ constant}^{\mathrm{Movement}} = AS^{\Delta L} \tag{3}$$

Which can be rearranged as:

$$\frac{F}{A} = S^{\Delta L} \tag{4}$$

The exponents can be simplified and separated to establish the relationship of movement with tension:

$$\log\left(\frac{F}{A}\right) = \log(S^{\Delta L}) \tag{5}$$

and,

$$\log\left(\frac{F}{A}\right) = \Delta L \times \log(S) \tag{6}$$

Finally resulting in the relationship for movement with cable loading, defined as:

$$\Delta L = \frac{\log\left(\frac{F}{A}\right)}{\log(S)} \tag{7}$$

The relationship presented in equation (7) defines the relationship presented between the reduction in yarding distance and the tension in a skyline, with factors L and S available given a yarding profile and a cable tension analysis. Knowing the anchor capacity against sliding, presented in equation (1), and the relationship between cable tension and movement, these relationships can be related to predict when a mobile anchor will slide forward and relieve cable tensions.

Knowing a given anchor capacity for a yarding configuration, it is possible to predict movement based on the LCCC when anchor capacity is exceeded. That is, when the cable load is less than that of the pre-

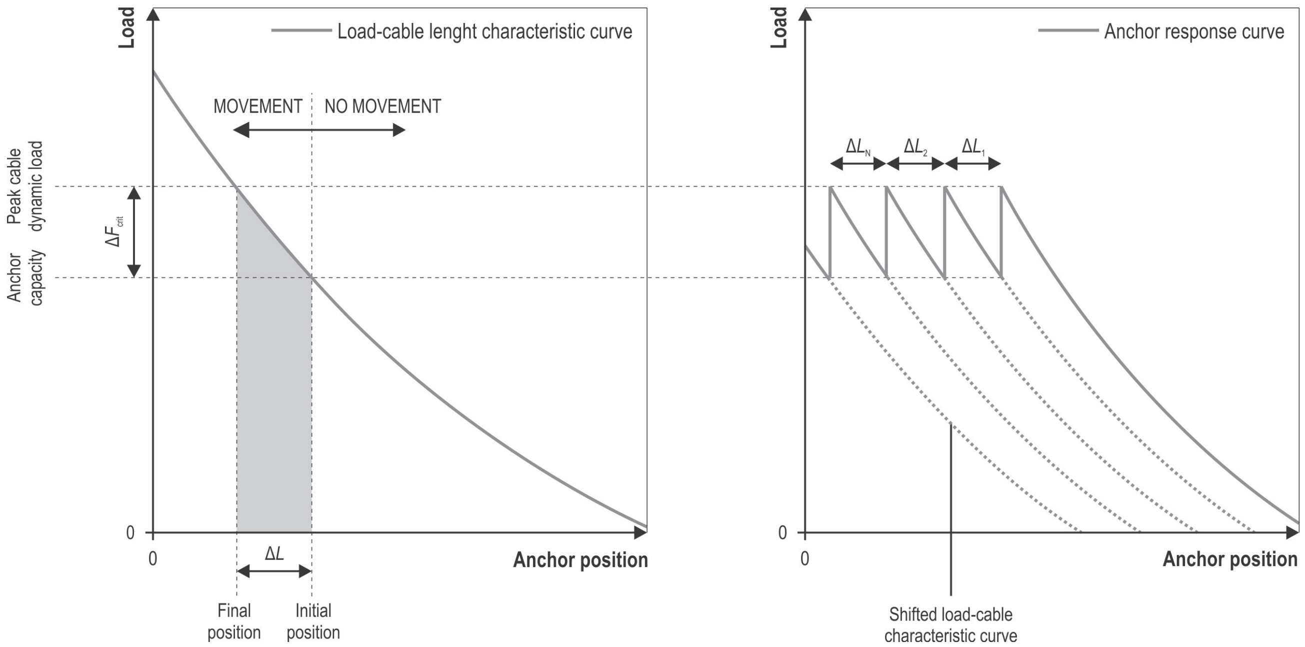

Fig. 3 (a) Left, Schematic representation of load-cable characteristic curve (LCCC) and (b) Right, the associated anchor response curve (ARC)

dicted anchor capacity, mobile anchor movement is predicted to be negligible. However, when cable tensions exceed the anchor capacity, the soil supporting the equipment will yield, enabling movement of the vehicle until it once again reaches equilibrium (Fig. 3a), represented by an Anchor Response Curve (ARC, Fig. 3b). Equilibrium occurs due to reduced cable tensions from increased cable sag, as well as the anchor capacity of the vehicle from soil shear. Often, this peak loading occurs due to dynamic loading during yarding, and after mobile anchor movement and cable tension relief, the system returns to equilibrium, and the anchor becomes immobilized once more (Fig. 3b). Upon repeated cycles of yarding payloads, yielding of soil beneath the mobile anchor tailhold, and subsequent movements, the vehicle moves forward notably (Fig. 3b) and may need to be returned to its initial position. After each movement, assuming a similar gradient for the mobile anchor, the LCCC is shifted accordingly. When the anchor capacity is exceeded again, then the same process occurs, predicting the relationship between movement, and anchor capacity based on the LCCC. When the equipment has shifted forward beyond the point of safety or function, it can be moved back to its initial position since the anchor is motorized and mobile.

From an analytical perspective, the ARC is determined based on calculated anchor capacity and a given LCCC, which present a piecewise function for mobile anchor movement when combined. The ARC follows a typical LCCC until the anchor capacity is exceeded, after which, it will move (*ΔL*) according to the amount of cable tension load that has exceeded the anchor capacity (ΔF_{crit}), as shown in Fig. 3a. Based on the LCCC and anchor capacity, the following relationship is demonstrated for movement:

$$\Delta L = \frac{\log\left(\frac{F_{\max} - F_{crit}}{A}\right)}{\log(S)} (F_{\max} > F_{crit}) \tag{8}$$

The gray, shaded portion in Fig. 3a represents when anchor capacity is exceeded and movement occurs, while the unshaded portion underneath the curve represents no movement. When the cable tension does not exceed the anchor capacity, no movement occurs. This is represented by:

$$\Delta L = 0(F_{\max} < F_{crit}) \tag{9}$$

Where:

F_{crit} anchor capacity

Thus, a piecewise function is presented to establish the ARC for a given LCCC and anchor capacity (F_{crit}).

The establishment of the anchor capacity to sliding and the load-cable characteristic curve enable a means of predicting the movement response, known as the anchor response curve (ARC). Knowledge of an ARC provides a means to design mobile anchor systems used for skylines to yield and move providing that

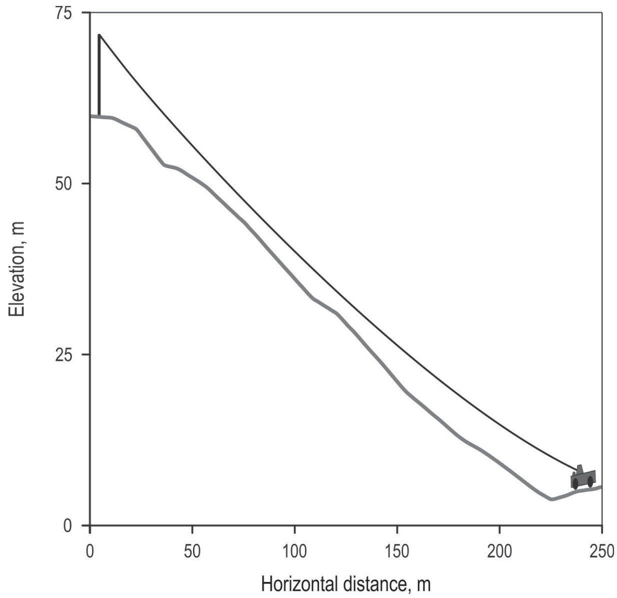

Fig. 4 Cable yarding system profile

anchor movement will have a safe run out distance. That is, with a known yarding profile, a known payload, and a known anchor capacity, sufficient equipment setback can be employed to prevent a loss of a mobile anchor. Such a design could ensure that cable tensions do not exceed the skyline design capacity and the yarding tower is not toppled due to guyline anchor breakage. This analytical method is verified with field testing, presented in this study.

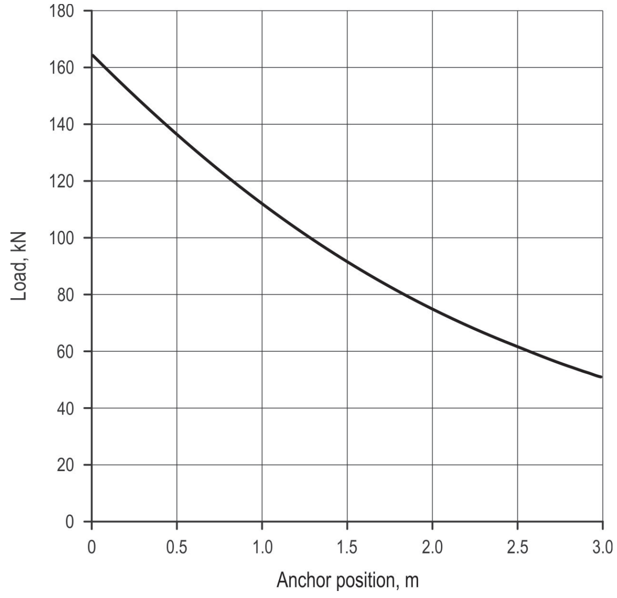

Fig. 5 Load-cable characteristic curve (LCCC) for given cable logging configuration

3. Field tests

A series of field tests were performed in the McDonald-Dunn forest in Oregon State University, intended to both verify prior analytical solutions for mobile anchor capacity and serve as the yielding point for anchor movement and skyline tension relief. The field tests were performed by instrumenting a swaged skyline (diameter = 1.9 cm, rupture capacity of 375 kN) anchored by a John Deere skidder, weighing 137.9 kN and supported by a wheeled undercarriage that was initially not embedded on the gravel surfacing. As it was dragged forward, slight embedment occurred, which was accounted for in anchor capacity calculations. The yarder was a Koller 501 Trailer, yarding an Acme 15 motorized carriage. The yarding profile is presented in Fig. 4. A cable load cell was placed directly on the skyline and recorded loading at a frequency of 20 Hz. After each successive yarding cycle, movement was measured between a fixed, stationary survey point on the ground to a fixed point on the vehicle. A LCCC was generated by determining the maximum load for a given yarding profile for the initial position and 0.25 meter increments of forward, horizontal movement towards the direction of pull. These points were then fitted using an exponential function, where *F* was 164 kN and *S* was 0.888 (Fig. 5). The anchor capacity for two similar scenarios is presented, and used with this LCCC to use the ARC to predict mobile anchor movement.

Test 1 involved mobile anchor conditions with a hillslope of 3.4 degrees, skyline angle of pull of 17 degrees, a subsurface of compacted road aggregate (ϕ=45°, γ=18.9 kN/m^3) with no initial blade embedment, resulting in a predicted anchor capacity of 122 kN. The presence of a rubber tired undercarriage led to no assumed, added cohesive shear forces along the base (no tracked suspension). Use of the LCCC and the ARC (i.e. equations 8 and 9) allowed a comparison of recorded movement to predicted movement based on recorded load and calculated anchor capacity for the given configuration (Fig. 6). The first loading cycle resulted in a dynamic load that approached the calculated anchor capacity, resulting in recorded movement. However, since the load barely exceeded the predicted anchor capacity, very little movement was observed from the ARC. However, subsequent cycles that exceeded anchoring capacity resulted in predicted movement that agreed relatively well with recorded movement for the equipment. The final movement for the five loading cycles was 1.60 meters and 1.65 meters for the recorded and predicted movements, respectively (Fig. 6). Note that the anchor capacity increased slightly with deepening blade embedment, approaching approximately 15 cm as the anchor shifted forward.

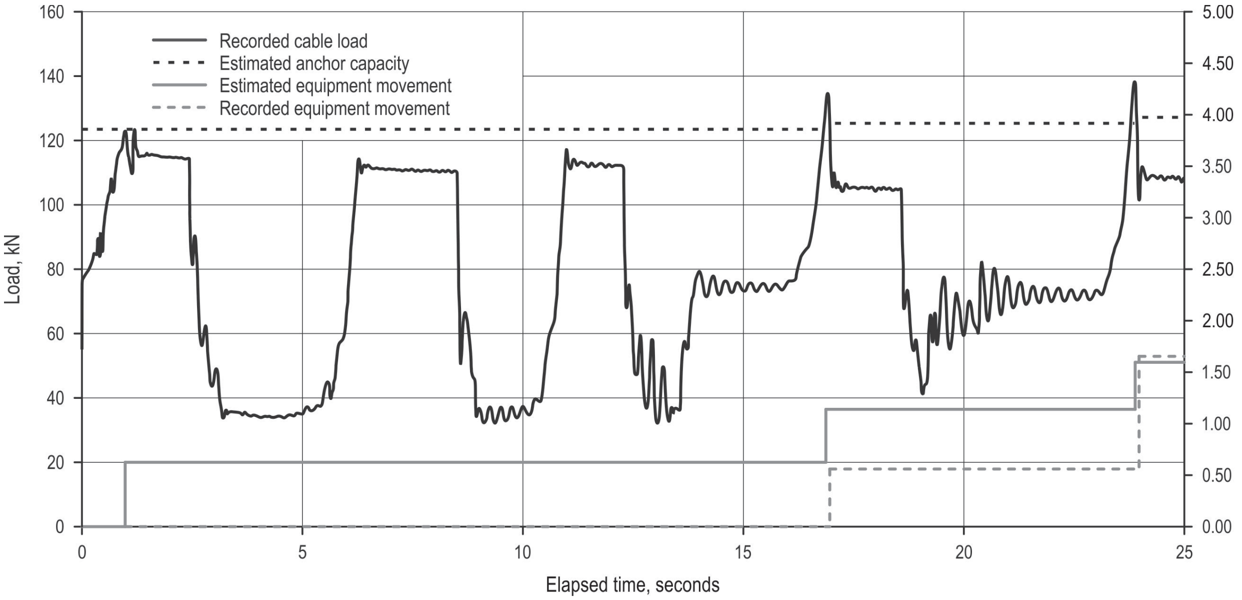

Fig. 6 Cable loading, recorded equipment movement, anchor capacity and predicted equipment movement for test 1 over a condensed timeframe (for clarity)

Test 2 involved mobile anchor conditions with a hillslope of 4 degrees, skyline angle of pull of 18 degrees, a subsurface of compacted road aggregate (ϕ=45°, γ=18.9 kN/m^3) with no initial blade embedment, resulting in a predicted anchor capacity of 122.2 kN. Use of the LCCC and the ARC allowed for a comparison of recorded movement to predicted movement based on recorded load and calculated anchor capacity for the given configuration (Fig. 7). The first two loading cycles resulted in a dynamic load that exceeded the predicted anchor capacity, resulting in movements similar to that predicted from the ARC. Later cycles that exceeded anchoring capacity resulted in predicted movement that exceeded recorded movement for the equipment, but fell within a reasonable range. The final movement for the loading cycles was

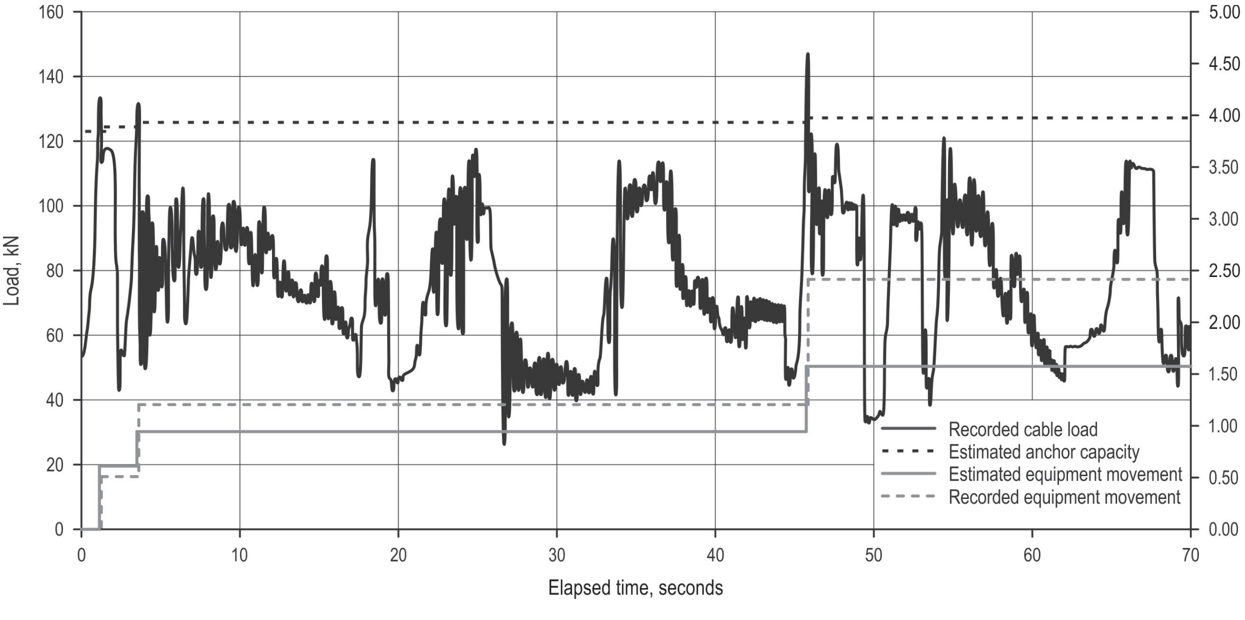

Fig. 7 Cable loading, recorded equipment movement, anchor capacity and predicted equipment movement for test 2 over a condensed timeframe (for clarity)

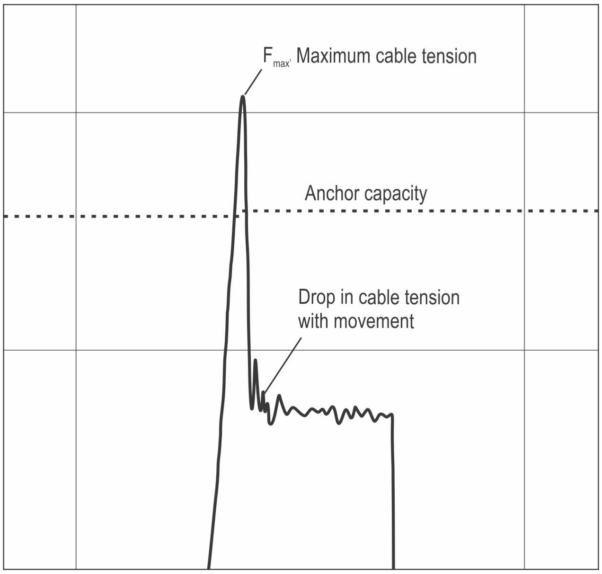

Fig. 8 Detail of cable tension relief and return to equilibrium with anchor movement

1.70 meters and 2.40 meters for the recorded and predicted movements, respectively (Fig. 7). Again, anchor capacity increased slightly with deepening blade embedment, approaching approximately 22 cm as the anchor shifted forward.

Recorded cable tensions showed a unique phenomenon when exceeding anchor capacity; specifically, a sharp drop in cable tension as the vehicle shifted forward to relieve loading. This drop in dynamic loading presents a relief for dangerous cable loads that may exceed safe working conditions for the skyline or yarder. As a large dynamic load occurs in the skyline, the tail anchor or yarder must give to the force – when the tailhold is free to slide, the tensions rapidly drop due to the increase in sag in the skyline (Fig. 8). As the equipment slides forward and cable tensions drop, the anchor capacity eventually becomes greater than the skyline tension resulting in a state of equilibrium again. This movement can be predicted using the LCCC and ARC, and subsequently can be developed into a design methodology preventing yarder overturning and skyline breakage if adequate clearance is given to allow mobile anchors to move.

Dynamic loading of the skyline played a significant role in anchor movement and accounted for a significant portion of loading. As yarding of a payload occurred, dynamic loads could be significant, accounting for up to a 41% increase in skyline tension compared with the subsequent return to equilibrium after anchor movement. Dynamic loading accounted for 7% to 41% of the total cable loading in scenarios where anchor capacity was exceeded. On average, the dynamic loading accounted for approximately 27% of the skyline tension, agreeing with prior studies (Jorgensen et al. 1977).

4. Conclusions

Tailhold mobile anchor capacity combined with the cable tension behavior of a loaded skyline enables a prediction of movement upon exceedance of soil resistance, presenting a means of relieving excessive cable tensions for safer yarding operations. The analytical solution based on a static-based anchor capacity equation (Leshchinsky et al. 2015) and a load-cable characteristic curve, easily determined from cable mechanics analyses or publicly available software (Skyline XL, USFS 2015), present a means of predicting movement for a mobile anchor. This prediction can be used for designing adequate clearance distance for a mobile anchor tailhold with a known skyline load. The following conclusions resulted from this study:

The predicted anchor capacity solution presented good agreement with field testing of mobile anchors employed as skyline tailholds. In the field tests, the predicted anchor capacity was within 15% of the actual loading when sliding failure occurred. This method of determining anchor capacity presents a means for designing mobile anchors for stability, or to yield under controlled conditions when skyline tensions may be relieved.

Combined use of the load-cable characteristics curve (LCCC) and mobile anchor capacity equation present a piecewise function (the anchor reaction curve, ARC) that presents a means of predicting the point at which an anchor will move, and quantifying approximate movement when it does occur. Inversely, the use of the ARC function with known cable loading, site conditions and yarding configurations will allow for appropriate clearance for mobile anchor application, ensuring safe yielding conditions without catastrophic failure or loss of heavy equipment in steep terrain.

When a mobile anchor capacity is exceeded, it may slide forward (when sliding conditions are critical and overturning is not a concern), relieving cable tensions by increasing the cable sag, eventually returning to equilibrium. Equilibrium is reached due to a relief in skyline tensions and an eventual recovery of soil resistance, sometimes occurring due to increased equipment embedment.

Dynamic loads within a skyline may contribute over 40% to the skyline tension in yarding. On average, when the mobile anchor failed, the dynamic loads accounted for 26% of the cable tension, subsequently decreasing back to equilibrium after yield. Yield was defined as sliding.

This study outlines an approach which may enable safer use of yarding systems due to mobile anchors serving as a tension relief system for a skyline. This function prevents excessive skyline loads and yarder overturning due to the sliding mechanism of the mobile anchor and subsequent reduction of tension. Like any design consideration, one must consider potential drawbacks in application. The most important consideration is that sliding failure must govern the mobile anchor application. Leshchinsky et al. (2015) presented a design approach that accounted for not only sliding failure, but overturning of mobile anchors, where the critical failure mechanism had to be accounted for. To employ yielding mobile anchors, it is critical to ensure that the maximum anchor resistance attained from the sliding mechanism is less than that of overturning. If sliding is not the failure mechanism, the equipment may overturn, resulting in a loss of function. Correct calculation of mobile anchor capacity involves an understanding of soil properties. It is important that the in-situ shear strength of the soil is estimated using reasonable methods. Mobile anchors require adequate clearance from dangerous drop-offs or slopes. Although movement can be predicted, the ARC is sensitive to extremely large loads and a sufficient buffer must be implemented to ensure that catastrophic movements do not occur. Like any design, conservatism in anchor setback ensures best results. Cable attachments must also be adequately protected from potential damage upon sharp surfaces on the equipment. Yielding and tension relief typically requires the use of lighter equipment with additional resistance provided by blade emplacement and possibly supplemental weights to match the design skyline tension. The use of very heavy equipment could lead to no anchor movement under significant skyline loads, placing the cable under potentially unsafe tension loads. Movement of equipment could change anchoring configuration and the interface properties between the machine and surface. Considerations need to be made based on available equipment, skyline selection and a given yarding profile. Despite these constraints, the use of mobile anchors presents a means of anchoring skylines that may improve safety as it does not catastrophically fail like stumps, buried deadmen, or plate anchors, and does not exceed safe working conditions for the skyline or yarding tower. The tension relief that occurs in the skyline due to enabling anchor movement may present a new alternative for increasing safety and efficiency of cable logging operations.

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Appendix

Table 1 The symbols and abbreviations used in this study

Symbol	Description	Units
A	Load factor	kN
A_t	Footprint area of vehicle	m^2
c'	Soil cohesion	kPa
D_b	Embedment depth of blade	m
F_{max}	Maximum skyline load	kN
F_{crit}	Calculated anchor capacity	kN
K_p	Passive earth pressure coefficient	–
P_p	Soil passive earth pressure in front of blade	kPa
S	Site constant	m^{-1}
T_g	Anchor capacity	kN
w_b	Width of embedded blade	m
W_t	Vehicle weight	kN
w_t	Width of tracks/tires (if applicable)	m
β	Slope angle	°
ΔL	Movement	m
γ	Unit weight of soil	kN/m^3
δ_t	Interface friction angle between vehicle base and soil	°
Θ	Cable angle of pull	°
ϕ'	Soil angle of internal friction	°

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