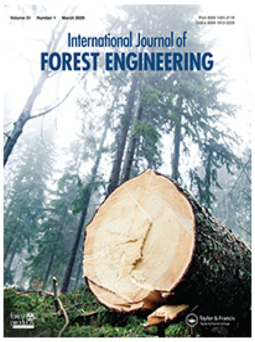

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Design of continuous bridle multiple-stump anchors

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ABSTRACT
This paper presents a solution for a three-stump anchor system using a continuous bridle and assuming frictionless blocks. This solution is unique in that the location of the bridle block is not known a priori. A particle swarm optimization was used to estimate the three coordinates of the bridle block and the tension in the bridle. A method employing trilateration was developed to locate the known points in the three-stump anchor system. The advantage to using this method is that only distances between known points need to be measured in the field (angles are not required). For two of the field cases, the ratio of skyline tension to bridle tension was close to the maximum of 6 (bridal tension reduction factor) that could be achieved given the three-stump anchor system, and the other case had a ratio of 4. It was found for shorter bridle lengths, the three-stump anchor system is more sensitive to how in lead the stumps are with the skyline. For three-stump anchor systems, the bridle tension is more strongly controlled by the location of the two outside stumps, and it is relatively insensitive to the location of the middle stump.

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Introduction

Visser and Stampfer (2015) note that cable-assist forest harvesting machines provide a reduction in harvesting cost and improvements in safety when harvesting forests on steep terrain. In the cable-assist systems the winch may be onboard the harvesting machine, in which case stumps or trees are often used to anchor the end of the cable upslope from the machine. In other cases, the winch is on board an anchor machine, and depending on the size of the anchor machine and the conditions it may be necessary to tie the anchor machine back to stumps. The use of cable-assist systems in steep slope logging has reinvigorated research in the strength of tree stumps used as anchors. Sessions et al. (2017) present a theoretical framework for the stability of tethered feller-bunchers and this work highlights the need for reliable tether anchors. Marchi et al. (2019) confirmed that it is difficult to predict the strength of stumps and trees used as anchors based on above ground dendrometric characteristics. They suggest using a nondestructive stiffness measurement to better estimate the strength of individual stumps. The difficulty in predicting the strength of trees and stumps used as anchors is a limitation for expanding the use of cable-assist systems and this has renewed interest in multi-stump anchors.

Toupin et al. (1985) considered four configurations for using two-stump anchors when single-stump anchors were not sufficient. Their results indicated a skyline connected to a bridle block riding on a continuous bridle connecting two stumps has a lower capacity than when the two stumps are in series. These results ignore the advantage where a continuous bridle running through blocks will balance the load on the individual stumps; this can be particularly useful when including more than two stumps in the anchor system. Oregon (2010) notes when using a continuous bridle to connect the anchor stumps to a skyline eye that the load is continuously redistributed as the lines stretch and move. When separate lines are used to connect the skyline to the anchor stumps, if the skyline load moves one anchor stump can drop out leaving the remaining stumps to carry the full load. Studier and Binkley (1974) present solutions for a system of multiple-stump anchors; however, their solutions assume the direction of the skyline tension and the bridle block is fixed and known. In practice, with asymmetric location of naturally occurring stumps, it can be difficult to predict the position of the bridle block before the system is loaded. In addition, blocks may have resistance to turning due to friction between the rotating parts and this will result in the tension of a cable changing as it passes a block. It is not known whether friction in the blocks will significantly affect the accuracy of models when the blocks are assumed to be frictionless.

The objectives of this paper are 1) to develop a method for solving for the location of the bridle block and the tension in the continuous bridle assuming frictionless pulleys for systems with more than two anchors, 2) to compare the estimated values to a limited set of field trials using three anchor stumps, and 3) to perform a parameter analysis that will provide guidance on bridle tension given skyline tension, anchor stump locations, and bridle length for three-stump anchor systems.

Methods and materials

Equilibrium equations

The general orientation of the three-stump anchor used in this paper is presented in Figure 1. In this system, the load on

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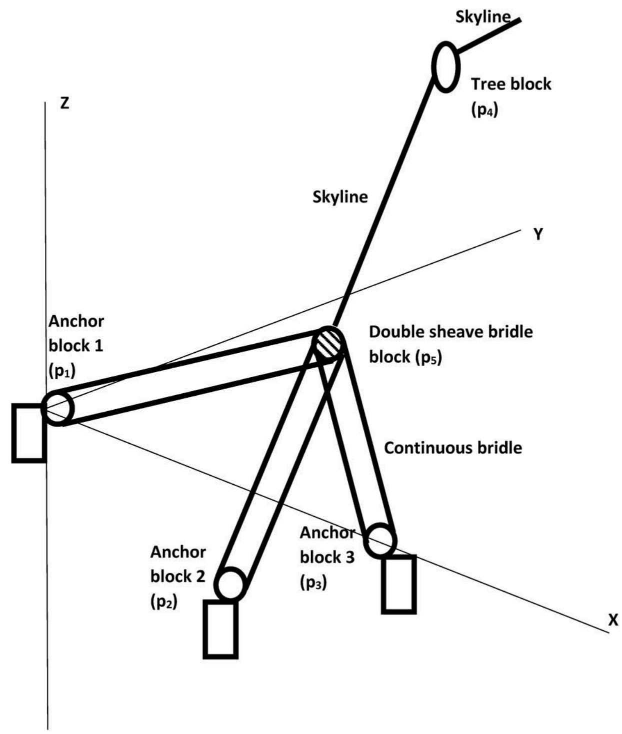

Figure 1. Three-stump anchor model.

the anchor is supplied by the skyline that is passing through a tree block. In practice, the load can be applied by any cable requiring an anchor, for example, a tether used in a ground-based harvesting system or a guyline. In the field tests performed for this project, we used a skidder with the winch cable passing through a fairlead in the arch as a substitute for a skyline. There are a number of variables and parameters used in this paper and in order not to confuse the reader we will consistently use the definitions provided in Figure 1, although the skyline could be any line requiring an anchor (e.g. guyline or tether for a ground-based system).

Let $\mathbf{p}_i$ be the location of the points in Figure 1, where $i = 1$ *to* 5. For $i = 1$ *to* 4 $\mathbf{p}_i$ are known, and the unit vectors between the known points and the unknown location $\mathbf{p}_5$ are given by

$$\mathbf{u}_i = \frac{p_i - p_5}{|p_i - p_5|} \text{ for } i = 1 \text{ to } 4 \tag{1}$$

Assuming the anchor blocks and bridle block are points, and assuming the tension in the continuous bridle is constant (i.e. the blocks are frictionless and line segments are weightless), the equilibrium equations given the cables acting on $\mathbf{p}_5$ are

$$\sum F_x = 2T(u_{11} + u_{21} + u_{31}) + Tsu_{41} = 0 \tag{2}$$

$$\sum F_y = 2T(u_{12} + u_{22} + u_{32}) + Tsu_{42} = 0 \tag{3}$$

$$\sum F_z = 2T(u_{13} + u_{23} + u_{33}) + Tsu_{43} = 0 \tag{4}$$

Here T is the unknown tension in the continuous bridle, Ts is the known skyline tension, and u_{ij} is the j$^{\text{th}}$ component of the i$^{\text{th}}$ unit vector. Let L be the known continuous bridle length, then

$$L = 2\sum\nolimits_1^3 |\mathbf{p}_k - \mathbf{p}_5| \tag{5}$$

Here $|\mathbf{p}_k - \mathbf{p}_5|$ are the vector lengths. Equations (2) to (5) provide a system of 4 equations with four unknowns; the three coordinates of $\mathbf{p}_5$ and the unknown continuous bridle tension T.

It can be seen from Equations (2) to (4) that

$$a = \frac{u_{4j}}{u_{1j} + u_{2j} + u_{3j}} \quad \text{for } j = 1 \text{ to } 3 \tag{6}$$

$$u_{4j} = a\left(u_{1j} + u_{2j} + u_{3j}\right) \tag{7}$$

Here a is a constant. Thus, substituting (7) into (2) it can be seen that T is a scalar multiple of Ts.

$$T = \frac{-aTs}{2} \tag{8}$$

In this paper, we examine a three-stump anchor system. This solution can be generalized to any number of stumps greater than two. Adding additional stumps with known locations does not add additional unknowns. Thus, the solution presented here still holds with (2) to (5) providing a system of four equations and four unknowns.

Equilibrium solution

Given the coordinates of $\mathbf{p}_5$ are contained in unit vectors, a numerical method was employed to estimate the coordinates of $\mathbf{p}_5$ and the tension of the continuous bridle (T). Particle Swarm Optimization (Eberhardt et al. 1995) was used to solve the system of equations. Particle Swarm Optimization (PSO) is a population-based heuristic search algorithm that has been used successfully in many nonlinear, nondifferentiable, and discrete optimization problems. Kaveh (2017) provides examples of applying PSO to problems in structural mechanics. The process begins with identifying a set of trial solutions (e.g. bridle block, locations, and tension) and then the Particle Swarm algorithm identifies the trial solution with the lowest error term and repopulates the space about this new best solution. The selection process is continued until a solution set is found that satisfies Equations (2) to (5) to an acceptable error.

Locating $\mathbf{p}_i$ in the field

For practitioners working in the field it is not practical to use survey instruments such as total station theodolites to locate $\mathbf{p}_i$ while setting up logging systems. An alternative method is the use of trilateration, which in three dimensions uses the intersection of spheres to locate points knowing only distances. The following is based on the derivation by Fang (1986). In the following D_{ij} is the distance going from $\mathbf{p}_i$ to $\mathbf{p}_j$. Once the system in Figure 1 is set up in the field, measure D_{ij} for $i = 1$ and $j = 2$ *to* 5; for $i = 3$ and $j = 2, 4,$ *and* 5; and for $i = 4$ and $j = 2$ *and* 5.

Let $\mathbf{p}_1$ and $\mathbf{p}_3$ form the baseline along the x-axis, and assume that $\mathbf{p}_1$, $\mathbf{p}_3$ and $\mathbf{p}_4$ form the x, y plane, thus

$$\mathbf{p}_1 = (0,0,0) \text{ and } \mathbf{p}_3 = (D_{13},0,0) \tag{9}$$

Taking D_{14} and D_{34} as the radii extending from $\mathbf{p}_1$ and $\mathbf{p}_3$ and that intersect at $\mathbf{p}_4$, then the coordinates of $\mathbf{p}_4$ are

$$p_{41} = \frac{D_{14}^2 - D_{34}^2 + D_{13}^2}{2D_{13}} \tag{10}$$

$$p_{42} = \sqrt{(D_{14}^2 - p_{41}^2)} \tag{11}$$

$$p_{43} = 0 \tag{12}$$

Now having the coordinates of $\mathbf{p}_1$, $\mathbf{p}_3$, and $\mathbf{p}_4$, and taking D_{15}, D_{35}, and D_{45} as the radii extending from the corresponding points and intersecting at $\mathbf{p}_5$, then the coordinates of $\mathbf{p}_5$ are

$$p_{51} = \frac{D_{15}^2 - D_{35}^2 + D_{13}^2}{2D_{13}} \tag{13}$$

$$p_{52} = \frac{D_{15}^2 - D_{45}^2 + p_{41}^2 + p_{42}^2 - 2p_{41}p_{51}}{2p_{42}} \tag{14}$$

$$p_{53} = \sqrt{(D_{15}^2 - p_{51}^2 - p_{52}^2)} \tag{15}$$

Using a similar method as for $\mathbf{p}_5$, the coordinates of $\mathbf{p}_2$ are found by

$$p_{21} = \frac{D_{12}^2 - D_{32}^2 + D_{13}^2}{2D_{13}} \tag{16}$$

$$p_{22} = \frac{D_{12}^2 - D_{42}^2 + p_{41}^2 + p_{42}^2 - 2p_{41}p_{21}}{2p_{42}} \tag{17}$$

$$p_{23} = \sqrt{(D_{12}^2 - p_{21}^2 - p_{22}^2)} \tag{18}$$

Field tension measurements

The objective of the field tests is to provide data to compare to the modeling results. The tests were performed using Douglas-fir (*Pseudotsuga menziesii*) that were approximately 50 years old, from the right of way of a logging road. In the following, spread refers to the distance between the two outside anchor stumps perpendicular to direction of the skyline. Three cases were considered; Case 1 modest anchor stump spread, Case 2 anchor stumps with narrow spread (e.g. in lead), and Case 3 wide anchor stump spread.

In the field trial, the anchor system was set up as shown in Figure 1 except for two differences, two blocks were shackled at $\mathbf{p}_5$ instead of a single double-sheave block, and a skidder winch was used in place of the skyline where the winch fairlead represented the tree block. The continuous bridle was 44.6 m long and was constructed of 9.5 mm (3/8 in) Ultrex rope with a breaking strength of 89,000N (20,000 lb). The reeving of the bridle block is shown in Figure 2. Two 35-tonne Straight Point Radiolink load cells were used to measure tensions. In the field tests $\mathbf{p}_5$ is a connection point. Load cell 2 connects the skyline to $\mathbf{p}_5$, load cell 1 connects the left end (as viewed in Figure 2) of the bridle to $\mathbf{p}_5$, the two single blocks that represent the double sheave block in the model are connected to $\mathbf{p}_5$, and the right-hand end of the bridle is connected to $\mathbf{p}_5$. Shackles and straps used to connect elements to $\mathbf{p}_5$ were kept as short as possible to limit the modeling error of considering $\mathbf{p}_5$ a point where all forces act. One was located at the end of the skyline (load cell 2) and one was connected to the left side end of the bridle (load cell 1) where it connected to the skyline. A steel Spencer's tape was used to measure the distances between the points. During the field measurements, the skyline was brought up to tension and held constant while the distance measurements were taken.

Modeling parameter analysis

A parameter analysis was conducted in order to better understand the effect of anchor stump location with respect to the skyline direction. As shown in (8), the bridle tension is a linear function of the skyline tension. Thus, the parameter analysis was conducted with a skyline tension of 1000N, and the results can be scaled to a skyline tension of interest. The bridle length strongly affects the bridle tension for a given set of stump locations. In the parameter analysis, the *L* is defined as

$$L = \frac{Lpercent}{100\%} * 2\sum_{1}^{3} |\mathbf{p}_k - \mathbf{p}_4| \tag{19}$$

Here, $0 < Lpercent \leq 100\%$. *Lpercent* is the ratio of the actual bridle length to the bridle length if the bridle block was located at the tree block location. For the tests, the bridle length was held constant and *Lpercent* is back calculated given the stump locations, tree block, and bridle length.

In the following the bridle reduction factor (*BRF*) is defined as

$$BRF = \frac{SkylineTension}{BridleTension} \tag{20}$$

Results

Field results

The model developed in this paper assumes the blocks used in the bridle are frictionless, that the tension in the bridle is

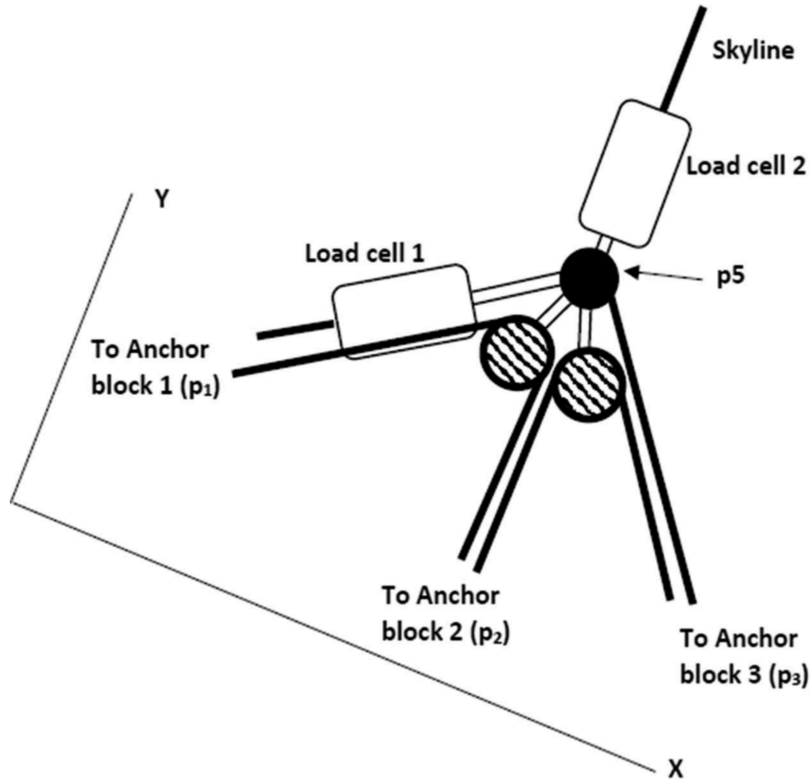

Figure 2. Reeving of the bridle block.

constant over its length (weightless lines), and that the blocks are of zero radius. Using the Case 1 anchor and skyline system, the load cells were inserted at either end of the bridle where the ends were shackled to the skyline eye. Figure 3 plots the tension on the right end of the bridle against the tension on the left, and it can be seen that a linear function explains 99% of the variation in the data. Equation (8) indicates that the bridle tension should be a linear function of the skyline tension, and for this to be true either the blocks must be frictionless or friction is a linear function of the skyline tension. The results from Figure 3 support the assumption that friction in the blocks is a linear function of the tension.

Figure 4 indicates there is a linear relationship between the bridle tension and the skyline tension for skyline tensions above 1000 N. For skyline tensions below 1000N, the lines began to sag and the directions of the cables and locations of the blocks changed with the skyline tension. This result supports the finding in Figure 3 that friction in the blocks is a linear function of the bridle tension. In Figure 4 the range of skyline tensions for Case 1 was lower than Case 2; however, these two cases have a similar $BRF = 6$. This indicates Case 1 and 2 are sufficiently close to being in lead that we are not able to differentiate them from being perfectly in lead given our measurement accuracy. Case 3 was sufficiently out of lead to have a noticeably different slope in Figure 4, and a $BRF = 4$.

Given (9) to (18), the distances measured between the points can be used to calculate the coordinates of the points for each of the three cases (Table 1). Using the point locations and the measured skyline tension, the bridle tension can be estimated by satisfying (2) to (5). The error in estimating the bridle tension as a percent of the measured bridle tension ranged from 5% to 12%. This error can be attributed to factors such as the accuracy of locating the points in the field, tension measurement error at the load cells, and friction in the blocks. Even though there is a noticeable difference between the measure tensions and the modeled tensions the error is an order of magnitude smaller than the measured tensions, and this indicates the model can provide useful information for understanding the behavior of the system.

When considering Table 1 results and comparing these to Figure 4, it becomes clear why Case 1 and Case 2 can have similar $BRF = 6$. In Table 1 *Lpercent* for Case 1 is 69%, while for Case 2 it is 35%. For a similar skyline and anchor orientation, a higher *Lpercent* would result in a higher *BRF*; however, in Case 1 the spread of the anchor stumps is greater than in Case 2. Thus, even though Case 1 has a wider anchor spread, the larger *Lpercent* results in a *BRF* close to that found when the stumps are in lead.

The bridle length used to estimate $\mathbf{p}_5$ and the bridle tensions in Table 1 was the unstrained length of 44.6 m. Figure 5 presents the estimated bridle tension for the three cases shown in Table 1 when considering percent strain. The bridle tension in Cases 1 and 2 responds similarly to increasing strain; the bridle tension drops by about 2% when going from 0% to 10% strain. In Case 3, the drop in bridle tension is more pronounced; 8% drop going from 0% to 10% strain. It is interesting to note that Cases 1 and 2 are more in lead and have a higher $BRF = 6$, while Case 3 has a wider spread in the anchor locations and has a $BRF = 4$. The wider spread results in a lower *BRF* and makes the system more sensitive to small changes in *Lpercent* and the resulting block location.

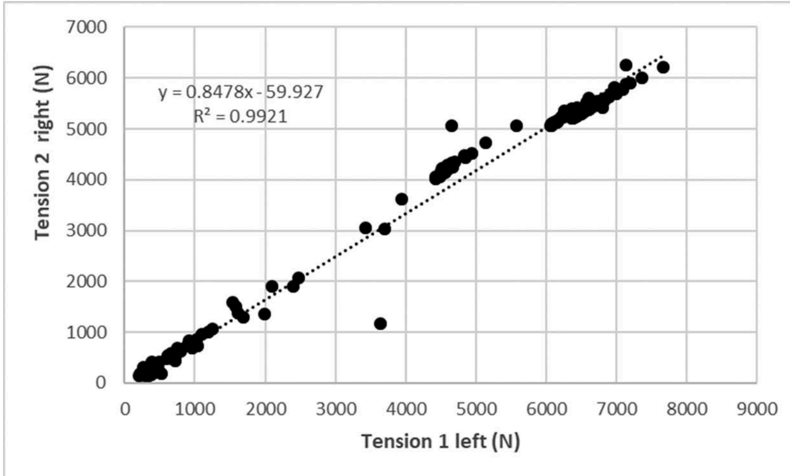

Figure 3. Testing for constant tension along the bridle.

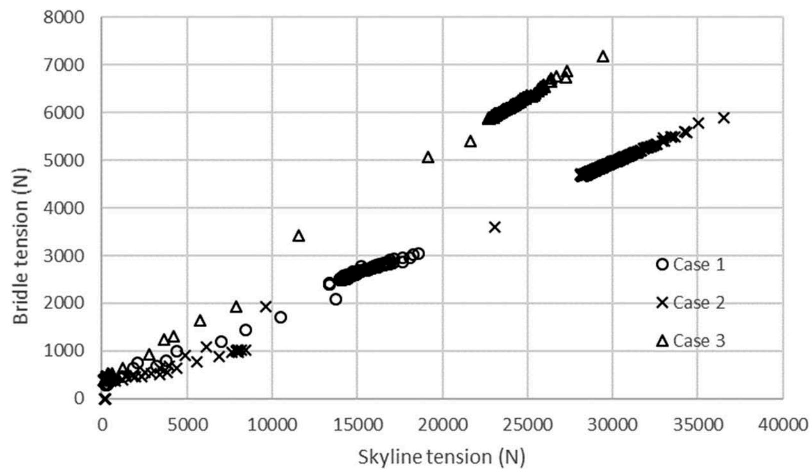

Figure 4. Bridle tension vs Skyline tension.

Parameter analysis results

The bridle tension (T) results are strongly affected by the bridle length for a given set of anchor stumps. Recall *Lpercent* is defined in (19). Two cases for the anchor stumps were selected to examine the effect of *Lpercent* on T. Case 4, where $\mathbf{p}_1 = (0, 0, 0)$, $\mathbf{p}_2 = (5, 0, 0)$, $\mathbf{p}_3 = (10, 0, 0)$, $\mathbf{p}_4 = (5, 15, 10)$, and Case 5, where $\mathbf{p}_1 = (0, 0, 0)$, $\mathbf{p}_2 = (5, 5, -5)$, $\mathbf{p}_3 = (10, 0, 0)$, $\mathbf{p}_4 = (5, 15, 10)$. Values for *Lpercent* ranged from 90% down to a value where the bridle was too short to permit $\mathbf{p}_5$ from being on the tree block side of all the anchor stumps. It can be seen in Figure 6 for *Lpercent* values above 50% that the difference between the two cases is relatively small; however, below *Lpercent* of 50%, the difference increases rapidly. It can also be noted in Figure 6 for Case 5, that the bridle was too short to be a feasible solution when *Lpercent* was below 40%. This is due to $\mathbf{p}_2$ being in front of $\mathbf{p}_1$ and $\mathbf{p}_3$ for Case 5, and thus the bridle block must be closer to the tree block in order to clear $\mathbf{p}_2$. The *Lpercent* that results in no feasible solution depends on the anchor and tree block locations being considered. Thus, it is not possible to generalize the *Lpercent* value that will result in no feasible solution.

Bridle tension (T) is also dependent on how in lead the anchor stumps are with the skyline. When the stumps are perfectly in lead and the blocks are assumed to be frictionless, then the bridle tension is one-sixth of the skyline tension (i.e. for $Ts = 1000N$ then $T = 167N$). Recall that the bridle tension is a function of *Lpercent* as this affects the angle of the bridle segments as they approach $\mathbf{p}_5$; however, the angle is also affected by the spread (distance between the anchor stumps perpendicular to direction of the skyline) of $\mathbf{p}_1$ and $\mathbf{p}_3$. In the following, we will use an *Lpercent* of 50% in order to consider a case where there is significant spread for a given location of $\mathbf{p}_1$ and $\mathbf{p}_3$. Figure 7 displays a range of $\mathbf{p}_2$ locations and the corresponding values of T, for $Ts = 1000N$. The maximum difference in tension is 10% (i.e. 184N to 202N) and this occurs when $\mathbf{p}_2$ is farthest off the plane created by $\mathbf{p}_1$, $\mathbf{p}_3$ and $\mathbf{p}_4$. When the vertical plane containing $\mathbf{p}_2$ is shifted 4 m in the negative x direction (i.e. the x coordinate for all the $\mathbf{p}_2$ considered is 1.0), the maximum increase in bridle tension is 3% (e.g. 202N to 208N). These results indicate for a set of three stumps with a wide spread for a given bridle

Table 1. Field tension measurements and comparison to model result. *Lpercent* is back calculated using the 44.6 m bridle length from Equation (19).

Case 1, pull perpendicular to x with modest spread	x1[a]	y1	z1	Measured Ts (N)	Measured T (N)	Modeled T (N)	*Lpercent*
p_1	0.00	0.00	0.00	17,638	2953	3257	69%
P_2	4.32	1.70	0.52				
p_3	8.71	0.00	0.00				
p_4	4.58	10.73	0.00				
p_5	4.15	5.57	0.11				
Case 2, pull in lead with x	x2	y2	z2				
p_1	0.00	0.00	0.00	33,501	5484	6161	35%
P_2	5.07	1.59	0.56				
p_3	9.38	0.00	0.00				
p_4	−11.93	13.08	0.00				
p_5	−1.91	4.33	0.36				
Case 3, pull perpendicular to x with wide spread	x3	y3	z3				
p_1	0.00	0.00	0.00	27,340	6877	6523	35%
P_2	1.39	−5.15	0.58				
p_3	10.92	0.00	0.00				
p_4	4.81	18.86	0.00				
p_5	3.65	5.16	0.54				

[a] x1 is defined by the line passing through p_1 and p_3, y is perpendicular to x in a right-hand coordinate system, and z is normal to the x-y plane.

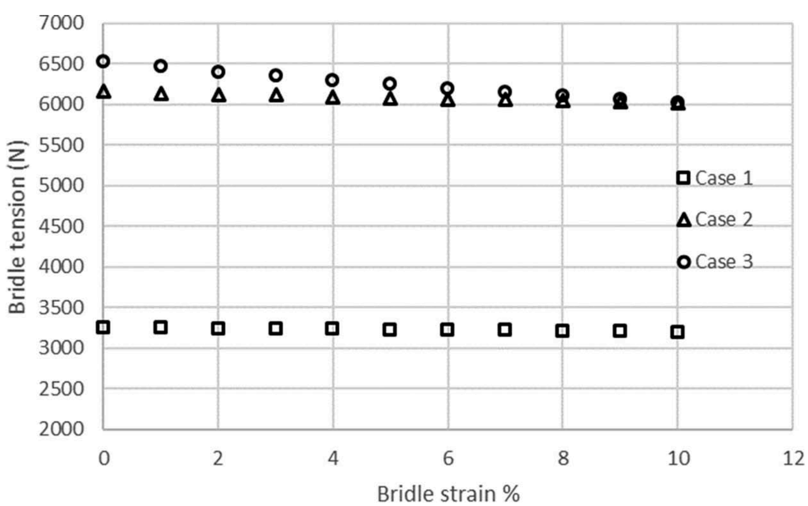

Figure 5. Bridle tension given bridle strain.

length that the bridle tension is relatively insensitive to how closely the middle stump (here this is $\mathbf{p}_2$) is in lead.

Discussion

Two important questions with using a continuous bridle with multiple anchor stumps include; a) is the tension relatively constant in the bridle resulting in equal loading of the stumps in the system, and b) for a given skyline tension what should the design bridle cable tension be? Figure 3 indicates there was friction in the blocks used in the system studied in this paper. The effect of friction appears to be constant for the higher tensions studied in this paper; however, to generalize this result, larger cables and blocks used at higher tensions should be studied. Even if additional data indicate this result with regard to friction can be generalized, it is important to remember when rigging these systems that care must be taken to ensure the bridle is running freely through the blocks.

The *BRF* depends on the spread of the anchor stumps and *Lpercent*. It was found in this study under reasonable anchor stump locations and *Lpercent* values that the *BRF* could range from 6 down to 4. Thus, it could be optimistic to assume the rigging configuration presented in Figure 1 will in practice result in a $BRF = 6$. In addition, the *BRF* is higher when the anchor stumps are in lead with the skyline direction rather than spread perpendicular to the skyline direction. When using a continuous bridle, selecting anchor stumps that are in lead is more important than symmetry (i.e. anchor stumps balanced symmetrically about the skyline).

Changing the strain in the bridle from 0% to 10% resulted in 2% to 8% change in the bridle tension. The change in bridle tension was more pronounced when the stumps were farther out of lead. Ten percent is a very large strain and not likely to be found in practice. In addition, estimating the effect of the bridle passing around the block as opposed to the modeling assumption used in this paper where the block was a point will result in a small change in the bridle tension. In fact, strain in

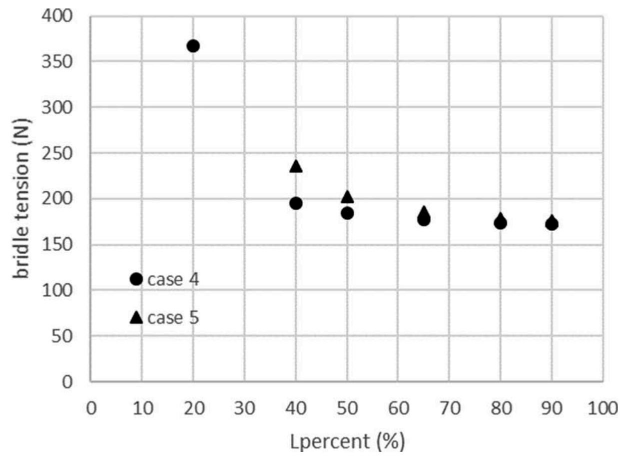

Figure 6. Sensitivity of bridle tension (*T*) to *Lpercent*.

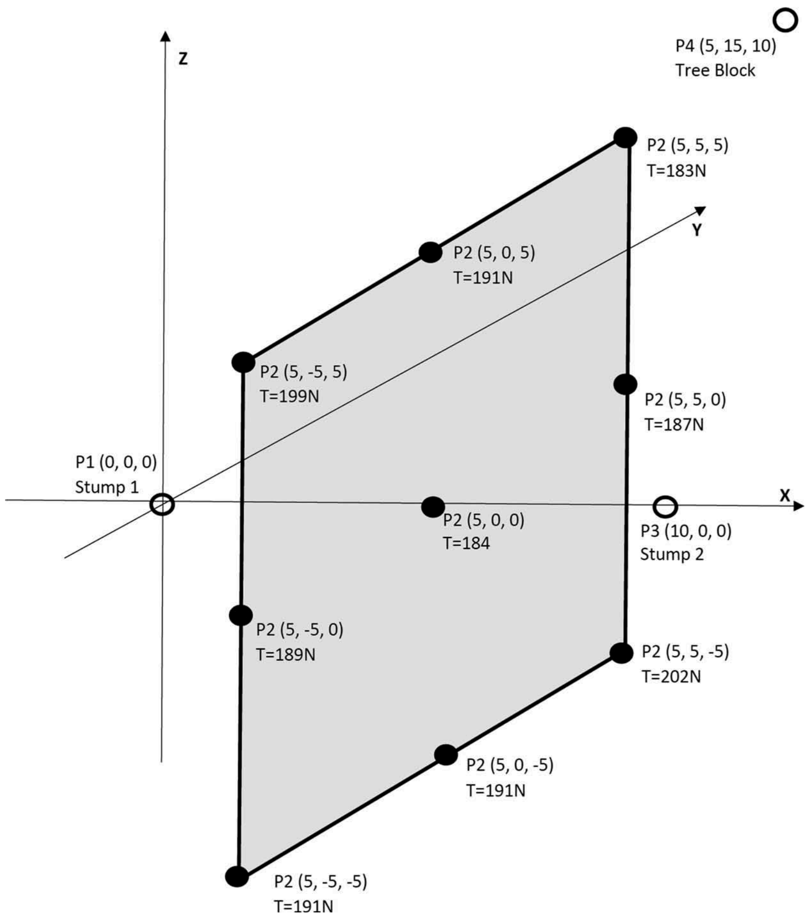

Figure 7. Bridle tension (*T*) given varying positions for $\mathbf{p}_2$. The skyline tension is 1000N and $Lpercent = 50\%$. For $\mathbf{p}_2 = (5, 0, 0)$ the location of $\mathbf{p}_5 = (5, 6.9, 4.6)$.

the bridle acts to offset the effect of the increase in path length due to block diameter. Thus, this paper indicates it is reasonable to consider the unstrained bridle length when estimating the bridle tension during setup in the field.

The procedures developed in this paper can be extended to include additional anchor stumps, where the additional anchor stumps are connected to the system through the continuous bridle. The additional anchor stumps are known locations, and though the system becomes more complicated, there are still only 4 unknowns (the three coordinates of the bridle block and the bridle tension). Thus, the three equilibrium equations and the length compatibility equation form a system of four unknowns and four equations.

When using individual straps to rig anchors with more than two stumps, it can be difficult to judge the required length of the straps before the system is loaded. Small errors in strap length can result is dramatic differences in strap tensions. One method to avoid this problem is to have a single anchor stump that is tied back with twisters to multiple additional stumps. When using twisters it is difficult to estimate the load that will be transferred to each stump; here the problem is the strain rates of the stumps and twisters. When using the continuous bridle, each anchor stump receives the same load per bridle segment that is attached to the stump. This is a great advantage in that it is not necessary to accurately estimate the position of the bridle block when it is loaded. In addition, if a lower load is desired for a particular stump, a single end of the bridle can be attached to that stump, this stump will only receive the bridle tension, rather than double the bridle tension if the bridle was to pass through a block at the stump.

Conclusions

This paper presents a solution for a three-stump anchor system using a continuous bridle and assuming frictionless blocks. This solution is unique in that the location of the bridle block is not known a priori. A particle swarm optimization was used to estimate the three coordinates of the bridle block and the tension in the bridle. A method employing trilateration was developed to locate the known points in the three-stump anchor system. The advantage to using this method is that only distances between the known points need to be measured in the field (angles are not required). The methods for locating the known points and solving for the bridle tension can be extended to systems with more than three anchor stumps provided they are connected to the skyline with a continuous bridle.

Three examples of the three-stump anchor system were set up in the field, and the tension in the bridle and location of the bridle block were measured. For bridle tensions above 5,900N the percent tension difference between the bridle ends was relatively constant at 20%. The difference between the modeled tension and the measured tension ranged from 5% to 12%, indicating that friction could be ignored when estimating bridle tensions before rigging. Bridle length and how in lead the anchor stumps are with the skyline tension will dictate the *BRF*. Two of the field cases had *BRF* that were very close to the maximum of 6 that could be achieved given the three-stump anchor system in Figure 1, and the other had a *BRF* of 4. This indicates assuming a *BRF* of 6 for the system in Figure 1 could be overly optimistic when sizing the bridle for a given skyline load.

When performing a parameter analysis on the three-stump anchor system it can be seen in Figure 6 for *Lpercent* values above 50% that the difference between the two cases is relatively small; however, below *Lpercent* of 50%, the difference increases rapidly. This suggests ensuring *Lpercent* is greater than 50% during setup is a useful guide; however, this limit would not be required if the three anchor stumps were all in lead. When considering three anchor stumps that are out of lead, the bridle tension is more strongly controlled by the location of the two outside stumps, and it is relatively insensitive to the location of the middle stump.

Visser and Stampfer (2015) discuss the increased use of ground-based systems on steep slopes. In addition to new anchoring requirements for the tethered machines, there will be the problem of elevated line tensions where yarders are lifting larger turns due to bunched logs from mechanized falling. As pointed out in best practice guidance such as Oregon (2010), it is critically important to balance the load on the stumps when using multiple stumps to anchor a line. The continuous bridle multi-stump anchor system automatically performs this important task if the blocks are sufficiently close to being frictionless. Additional work is required to confirm the effect of friction in the blocks on the tension in the bridle. Larger blocks at higher tension should be tested to determine if friction remains a linear function of tension. In addition, the condition of the blocks should be considered; new vs old, and greased vs not greased.

Disclosure statement

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