

DEPARTMENT OF FORESTRY ENGINEERING

INVESTIGATION INTO THE COEFFICIENT OF FRICTION
BETWEEN LOGGING WIRE ROPES AND TREES

By

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RUNNING HEAD: Coefficient of Friction Investigation

ABSTRACT

Cable-assist harvesting systems frequently use trees to change the angle of the wire rope to optimise harvest operations. The act of running the wire around the tree instigates a friction between the two materials which changes the tension in the rope. This project investigates this important friction interaction by pulling three logging ropes around a section of wood. The three ropes included a 13mm swaged wire rope, 13mm conventional non-swaged rope and a 9mm conventional non-swaged rope and these were all wrapped around two logs. This project explores the relationship between the tension in a rope and coefficient of friction between the two materials. The main theory behind this relationship is the Capstan Equation. This equation relates the coefficient of friction, wrap angle and rope tension between the wire rope and a log substituted as a tree. Testing was completed in the University of Canterbury Forestry workshop and looked at parameters such as rope type, wrap angle, log condition and notching, and finally log diameter. It was found that the different rope sizes have a different coefficient of friction, and the swaged and non-swaged ropes also had different results. The coefficient of friction for each rope is calculated and the two larger ropes are run through a manually cut U-notch to investigate the effect of the increased contact area on the coefficient of friction. The two log diameters are compared and the increase in diameter between the two logs has very minimal effect on the results. The validity of the results is discussed due to the down scaled nature of the experiments compared to the forces generated by real systems. Alongside this discussion is a review of the experimental procedure and possible further research opportunities relating to this project.

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1. INTRODUCTION

Wire ropes have been used in the logging industry for decades. The most common use for these ropes is within cable logging systems. In general, these ropes are used to pull logs from where they are felled to a landing. Cable logging systems generally involve a skyline with some butt rigging and chokers or a mechanical grapple, therefore cables are rarely run along the ground or around obstacles. A relatively recent invention in the logging industry is the winch-assisted felling machine. This system typically includes three machines. The first is a winch machine such as a dozer or a digger, the second is a felling machine and third a wire rope. This wire rope connects the two machines and is now used in an environment which is a lot harsher than standard cable logging. This is due to the fact that these cables get pulled along the ground and around trees. When wrapping a cable around a tree, there is a difference in the tension between the two ends of the cable in contact with the tree. The tree applies a resultant normal force and therefore a frictional force into the cable. The tree is acting in a similar way to a capstan or bollard and therefore Eytelwein's (or Capstan) equation can be used to estimate the coefficient of friction if the tension on both sides of the tree are known alongside the wrap angle of the rope. We can use this equation to look into improving our knowledge of the relationship between a wire rope and the exterior of a tree. It is possible to estimate a static coefficient of friction for a wire rope on the exterior of a log by doing some laboratory tests using a relatively simple rigging set up. Scaling this model down to a workshop sized experiment will limit the application of these tests to the real world cable-assist situations however it should build on a very limited area of knowledge involving wrapping wire ropes around trees.

2. OBJECTIVES

The goal of this research project was to improve our knowledge of the behaviour between wire ropes and trees by:

- Investigating the coefficient of friction of a wire rope wrapped around the exterior of a radiata pine log.
- Explore the effect that angle, rope type, rope size, log diameter, and log condition has on the coefficient of friction.

3. METHODOLOGY

3.1 Literature Review

A very important concept within the physical fields of static and kinetic motion is friction. Friction is defined as “The resistance that one surface or object encounters when moving over another” by the

Oxford Dictionary (Oxford Dictionary, 2016). The coefficient of friction is an important aspect when looking at the science surrounding friction. This report will not go into specific details behind the science of friction however the following diagram outlines the basic principles. These include a contact area along which the friction force acts and the normal force acting perpendicular to the direction of movement which acts at a certain angle (θ) to the force of gravity.

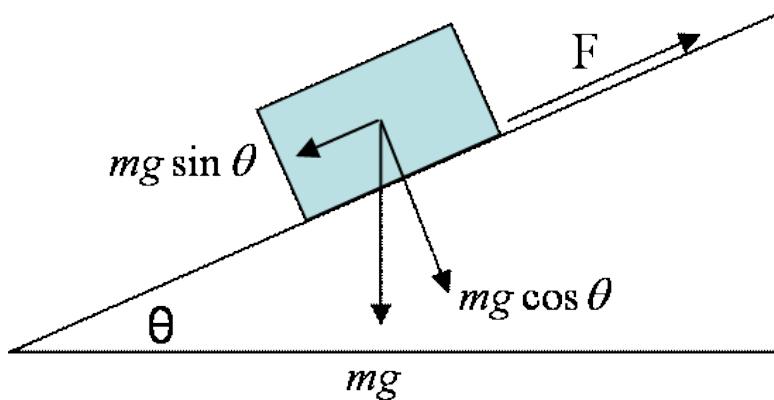


Figure 1: Standard friction example

A coefficient of friction is defined as “the force required to move two sliding surfaces over each other, divided by the force holding them together.” (Dictionary.com, 2016). The frictional force opposes the force which is moving the object and therefore acts in the opposite direction.

Wrapping a rope around a circular object is not a new practice as it has been done for many years in industries such as mining, marine or sailing and lifting. Most industries look at wrapping ropes around pulleys or blocks as they provide frictionless properties. A less common practice is to run a cable around a motionless sheave however this is still generally done with a wire rope on a steel sheave. However, industries such as marine (sailing), arboriculture and now logging must wrap different materials around each other which leads to much higher frictional forces and a different coefficient of friction. It is much harder to determine a coefficient of friction around a circular object than the basic case seen in Figure 1 above. The marine industry has looked at the tension difference when wrapping a rope around a capstan and this lead to the equation published by Eytelwein to become more commonly known as the Capstan Equation.

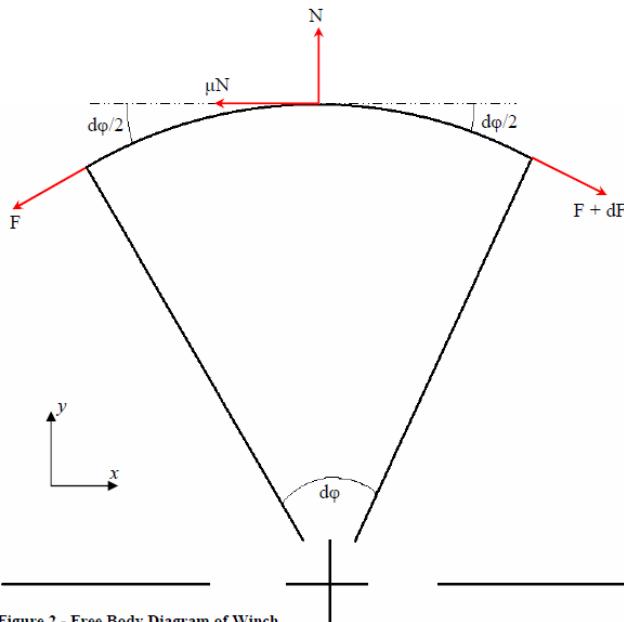


Figure 2 - Free Body Diagram of Winch

F an anticlockwise circumferential tension force

$F+dF$ a clockwise circumferential tension force

N a radial outward normal force on the element

μN a friction force on the element, where μ is the coefficient of friction

Figure 2: Free body diagram of a winch system with a cable wrapping around the exterior of a circular object. This relates the fundamental ideas of friction to a circular surface. Retrieved (Fulton, 2005).

The capstan equation is derived from Figure 2 above and relates the basic principles seen in Figure 1 to a circular surface with a wire wrapped around it. The relationship is used in multiple marine applications such as mooring or rope rescue. The equation is as follows (Chaplin, 1995):

$$T_2 = T_1 e^{\mu \theta}$$

Where:

T_2 is equal to the tension applied in the direction the rope is moving.

T_1 is equal to the resulting tension.

μ is equal to the friction coefficient of the sliding surface.

θ is equal to the angle that the rope is wrapped around the tree in radians.

The equation outlines that there is a direct relationship between the tensions in the rope, the coefficient of friction and the total angle of contact. These parameters are what appear to effect the friction force. This means that the solution is independent of the radius of bend and the size of the

rope. However, the friction of a rope between a rope and sheave can differ by a lot depending on the rope conditions (Attaway, 1999).

The same equation has been used for wire ropes in mine shafts to calculate the holding force of a winch as the rope winds further onto the drum. The variation in tensions are locked in as the rope takes its position wrapped around the drum and the change is balanced by the frictional force determined by the same capstan equation (Chaplin, 1995).

Research suggests that friction coefficients vary with loads, sliding speeds and contact pressure however these need to vary substantially to influence friction coefficients. Material properties of the surfaces in contact are a large influence on the friction coefficients (Kane, 2007). A study done on the ropes used in arboriculture being wrapped around cambium rings used the same method proposed in this project to define the frictional coefficient- both static and kinetic- of synthetic arborist ropes on metal cambium rings. The test was done by applying increasingly known weights to the rope until it moved with the resulting tension monitored by a load cell. The point of movement occurred just after the maximum static coefficient of friction which coincides with the maximum load applied (Kane, 2007). This study did not collect any data about the coefficient of friction of the ropes on the tree branches themselves and noted that it would require further testing to do so.

The capstan equation has only been applied once before in quotable literature within the logging industry. The paper written by Kimbell (1981) involved wrapping a wire rope skyline 360 degrees around a stump and then back to a tie-back stump and then measuring the tension difference on either side of the stump. Kimbell (1981) looked at the coefficient of static friction for 3/4 and 7/16 inch diameter rope when wrapped around a stump inside a notch. This is a very useful piece of literature as it concludes that in certain testing situations, the cable diameter does influence the coefficient of static friction as a 0.25 inch increase in cable diameter will increase the coefficient of static friction by approximately 0.0144 (Kimbrell, 1981). This was determined by applying the results found and then inputting them into a modelling software and looking at the regression found.

One large difference between Kimbell's (1981) study and my research proposal is the inclusion of a notch, which potentially means the cable diameter has a larger effect than if it was just running alongside the exterior of a tree due to the increased contact area against the tree. This could be an anomaly which contradicts the Attaway study claiming the friction coefficient is independent of the cable size (Attaway, 1999). The study used an adaptation of the equation to incorporate the fact that their test was using a notch in the stump:

$$T_2 = T_1 e^{\frac{\mu\theta}{\sin(\beta)}}$$

The $\sin(\beta)$ term incorporates the interior angle of the stump and applies this to the wrap angle and coefficient of friction factor due to the large influence in the determining the results.

Another paper looked into the synthetic ropes used in the marine industry and used the capstan equation for a pair of capstans on a wharf. Brown (1977) determined the required amount of wraps needed to hold specified tensions with a known coefficient of friction, proving that the equation can be used in a multitude of applications. This means that if the coefficient of friction is known it can be used to calculate both the tensions and the required amount of wrap to achieve the desired results.

Using synthetic ropes is a much more common practice as they are a widely used in sailing. Flexible synthetic ropes are wrapped around winches and capstans for rigging. Winch design and efficiency has long been an aspect of competitive sailing, therefore understanding the relationship between the capstan and rope has been researched multiple times.

There are many different types of winches used in sailing and Murray Walker looks at the capstan equation as a method of investigating their performance (Walker, 2006). Parameters such as rope cross section and winch type were investigated using the set up seen in Figure 3.



Figure 3: Test rig set up used to investigate ropes on winches using the capstan equation (Walker, 2006).

This study used the above set up to estimate the coefficient of friction of the rope on the winch by incorporating the known tensions and wrap angle into the capstan equation. It was used to compare three rope types each with three rope sizes. Another study uses this same set up to investigate the relationship between capstan surface and coefficient of friction by using wrap angle and two known tensions.

The study found that knurled and horizontally grooved surfaces have a higher coefficient of friction than the equivalent smooth surfaces with coefficients of frictions ranging between 0.1 and 0.2 (Cameron-White, 2007). The author also found that after a wrap angle of 420 degrees (approximately 1.2 full wraps) the coefficient of friction started to decrease in value. This result was put down to experimental or human error.

Something to note when wrapping the rope around a capstan or winch multiple times is that the rope-on-rope contact of a multi turn configuration might influence the capstan equation and coefficient of friction. A study done by Alasdair Fulton (2006) investigates this effect. The study outlines the possible compression around the winch body by the rope being wrapped and tension being applied in two different directions. This could increase the surface contact area and therefore the coefficient of friction would increase proportionally (Fulton, 2005). Fulton (2005) used a known weight and a load cell on a variable angled plate to change the wrap angle which was used to estimate the coefficient of friction. The testing apparatus can be seen in Figure 4.

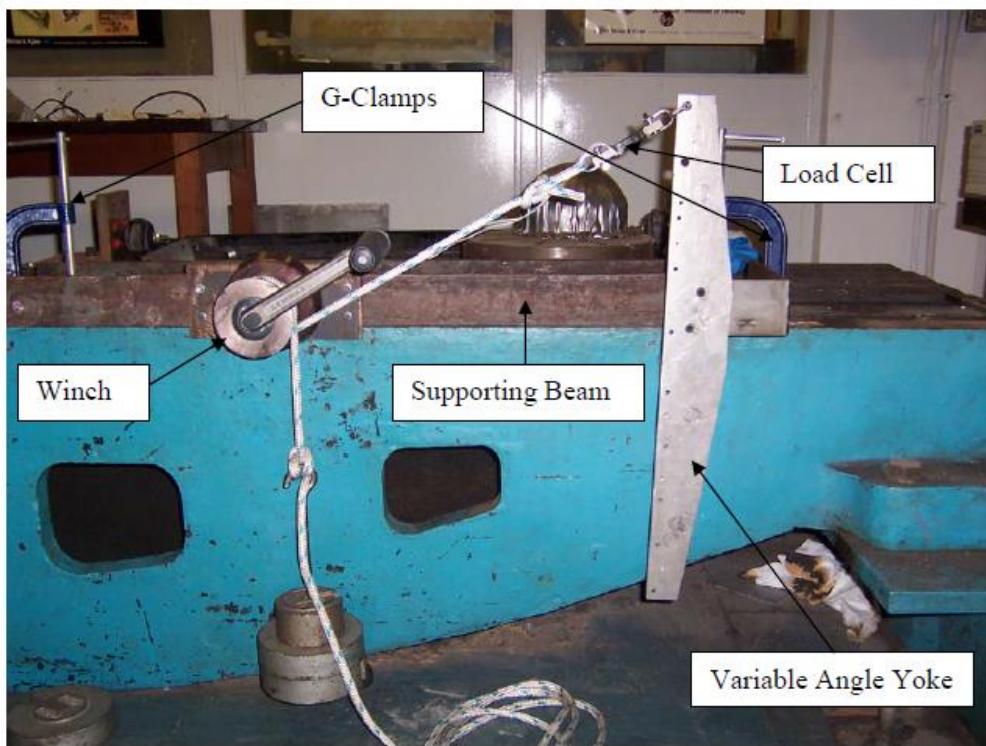


Figure 4: Example of a winch design to estimate the coefficient of friction with multiple wraps (Fulton, 2005).

The system utilised a computer to measure the force acting on the load cell at which the static friction transitioned to dynamic friction. This point corresponds to the highest coefficient of friction (or static coefficient of friction) and therefore was logged as the coefficient of friction for each test. Using the load cell required specialist computer software on a Strawberry Tree data logging board which was connected to a PC. This is a more technical way of measuring the two different tensions

on either rope as the winch had to be cranked in this particular test. For the testing done in my honours project, adding weight to one end to the point of slippage will achieve the same results.

All the studies above follow a similar outline and use the capstan equation which is encouraging for the validity of my testing procedure. All the studies look at calculating the coefficient of friction using this same equation, whether with a notch or not.

3.2 Testing Preparation

The initial part of this project involved investigating previous literature which looked into wrapping cables around motionless sheaves such as capstans and bollards or even trees to define projects or research that had been done to date. None of these papers investigating wrapped a wire rope around the exterior of a tree. However, the previous study on anchor tie backs for hauler rigging provided a starting point to build upon. In this case, the cable was inserted into a notch and the tension was monitored on either side of the stump. All the studies incorporated the capstan equation in one way or another to determine their results. Therefore the capstan equation will also be the basis of this study for estimating the coefficient of friction between a wire rope and a Radiata Pine tree/log. This is written as:

$$T_2 = T_1 e^{\mu\theta}$$

Where:

T_2 (Or T_{Load}) is equal to the tension applied in the direction the rope is moving.

T_1 (Or T_{Hold}) is equal to the resulting tension.

μ is equal to the friction coefficient of the sliding surface.

θ is equal to the angle that the rope is wrapped around the tree in radians.

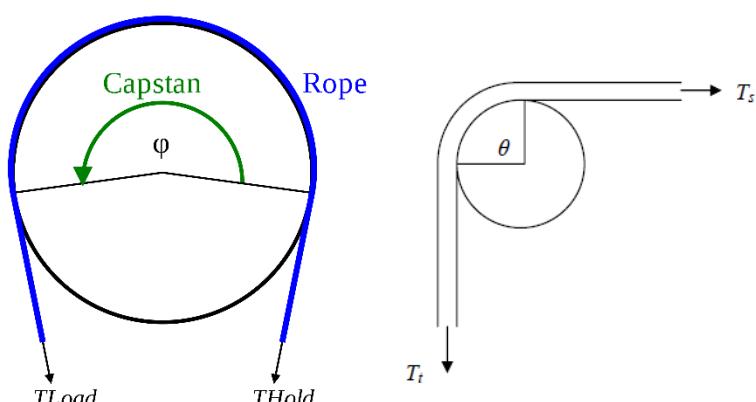


Figure 5: Examples of situations where the capstan equation is applicable (Fulton, 2005)

3.3 Testing Apparatus and Materials

Testing was done in the Forestry workshop in a similar set up to those outlined in the found literature. Using the workshop meant that the roof mounted crane could be used in place of the engine crane that was initially going to be used. This meant a testing procedure and health and safety outline had to be written up and submitted to the workshop supervisors Nigel Pink and Lachlan Kirk. A sketch of the system was submitted with this plan so that the workshop supervisors could set up a testing station that was strong and stable enough to ensure safe operation of the equipment.

Instead of monitoring tension with a tension monitor, an easier and faster method involved weighing the extra weight that was added to move the system at one end. The log was screwed into a piece of ply attached to a table which was bolted into the ground to avoid table movement when the cable was put under tension. To stop the crane from moving, it was strapped back to anchor points which left the system in equilibrium. The set up can be seen in Figure 7 below.

By using a pulley that was well lubricated, the tension on either side of the ‘frictionless’ pulley could be assumed to be equal, therefore the tension known below the pulley would be the same as the horizontal rope touching the log.

Sandbags were used as the weights in these tests. Bags were measured out at 25kg and tied up and regularly checked to ensure they hadn’t changed weight with a change in moisture content. Using two bags on either side loaded the wire rope up to 100kg of overall tension (50kg either side), while four bags on either side was used for the 200 kg loading scenarios (100kg either side).



Figure 6: Testing Apparatus Set Up

With this set up it was possible to test more than one rope type, so therefore 3 ropes were purchased from Bridon. Three ropes were bought to be tested- one 13mm (1/2") Blue Strand

Swaged Rope, and a 13mm and 9mm (approximately 1/2" and 3/8" respectively) Blue Strand Conventional Rope. All these ropes have a 6x26 structure, however the two conventional ropes are not swaged so this provided an opportunity to see if there is much difference between rope types.

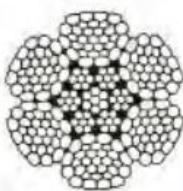
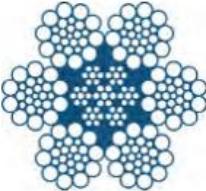
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Figure 7: Bridon wire rope types and diameters (Bridon, 2011)

The three ropes were eight metres in length from eye to eye and each rope had two pressed eyes at either end which allowed the ends to be attached to shackles and strops for adding weight. The outline of the three ropes are presented in Table 1 alongside their respective breaking loads.

Table 1: Wire Ropes used in the testing. Size, type and minimum breaking load quoted from Bridon's Catalogue.

Cable Diameter (mm)	Cable Type	Minimum Breaking Load (tonnes)
13	Blue Strand Swaged	15.3
13	Blue Strand Conventional	10.8
9	Blue Strand Conventional	5.39

These ropes were wrapped around two logs that were retrieved from the field in the Canterbury area. The logs had different diameters and were recently harvested and had been debarked. The logs were kept in similar conditions to minimise the differences between the two apart from diameter size.

3.4 Testing Procedure

During testing, all trials followed the same procedure outlined below:

1. Apply small increments of weight to the side under the crane.
2. Use sand as a smaller incremental change if needed.
3. Apply weight until system slips. The rope will slip in the direction of the weight applied, moving the weight at the crane end downwards and the weight at the log end upwards. The movement will cause the weight to fall and hit the ground, which will signal the end of the test.
4. Repeat set up for second trial.

Steps one and two were done by adding metal weights to add the majority of the weight, followed by filling bags up with sand to reach the point of slippage. An example of this can be seen in Figure 9 below.

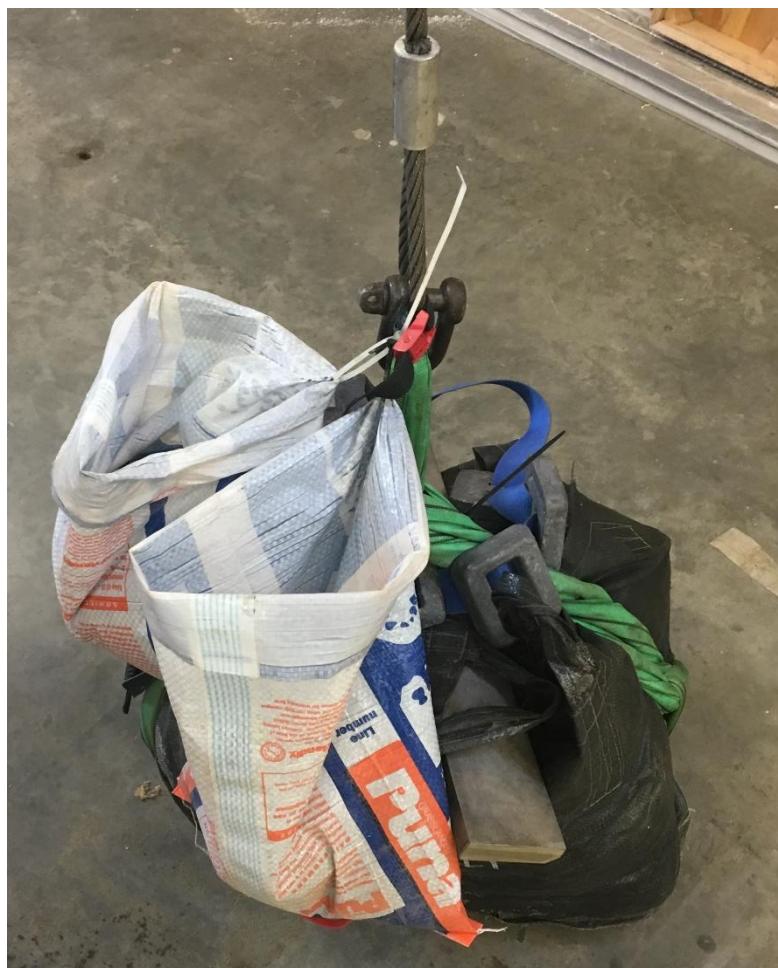


Figure 8: Example of the weight applied to crane end to cause the system to move with 100kg starting weight on either side

The above example shows the extra weight that was applied to move the system with a 200kg loading in the rope. The black bags contain 100kg of sand, the two green straps weighed one kilogram each, and then large metal weights were added to get closer to the slipping point. The two white bags were then filled with sand until the system moved. All these items were weighed on the workshop scales and the result recorded down. For each set up, a minimum of 3 trials was completed so that the average amount of added weight could be calculated for each scenario.

The test set up changed to investigate the effects of loading, wrap angle, log diameter, rope type and log condition.

3.4.1 Wrap Angle

To investigate the effect of wrap angle on the coefficient of friction, the 3 ropes were tested at a wrap angle of 90 degrees and 45 degrees. To obtain a 90 degree wrap angle, the pulley was kept level with the height of the log so that the total contact angle was as close to 90 degrees as possible.



Figure 9: Testing set up at 90 degree wrap angle

To set up for a 45 degree wrap angle the pulley was lifted higher up using the crane so that the rope left the log at an angle very close to 45 degrees. This meant that the internal wrap angle of the rope will be approximately 45 degrees and therefore it would be possible to see the difference in weight required to move the system in comparison to the 90 degree wrap angle. These comparisons were done with 50kg attached to either end of the rope. This meant that the total loading in the wire rope

was 100kg for both the 45 degree and the 90 degree comparisons. Figure 11 is a photo of the 45 degree angle set up.

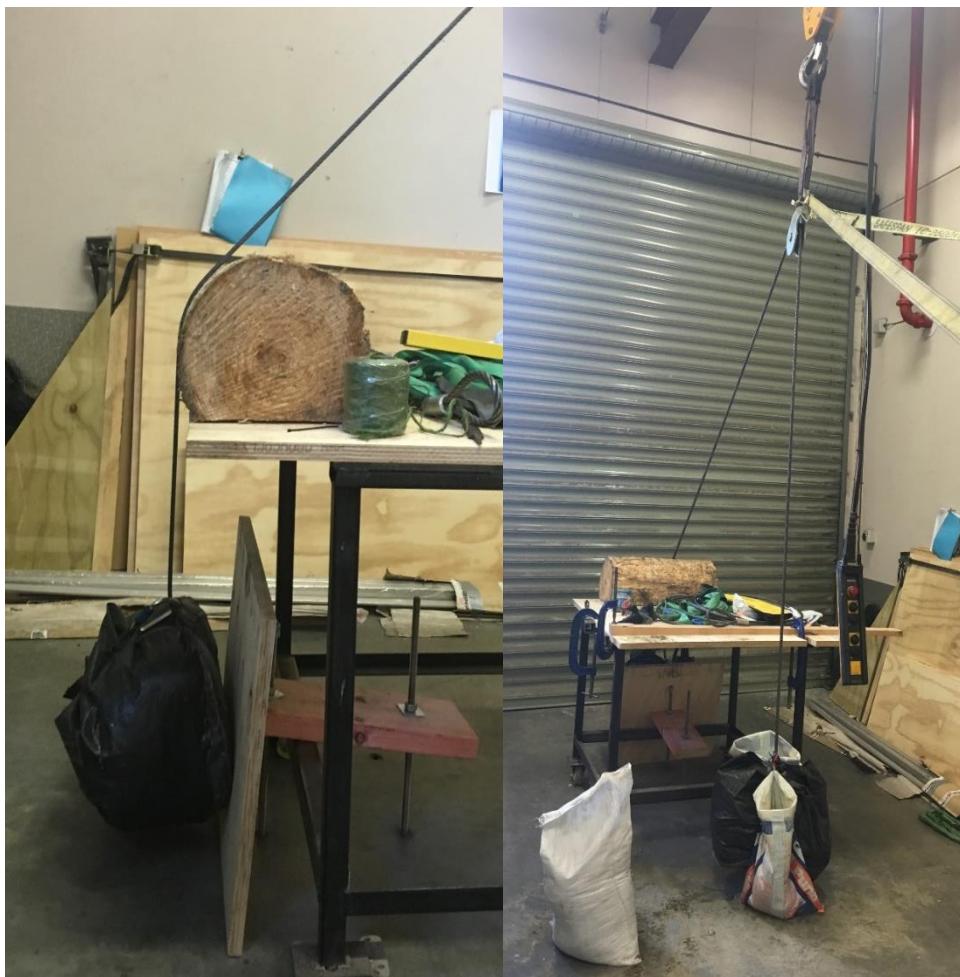


Figure 10: 45 Degree testing set up. Wrap angle (Left). Crane and rigging set up (Right).



Figure 11: Angle of Rope when under tension for 45 degree testing

3.4.2 Rope Loading

To test the effect that the loading has on the coefficient of friction two different test weights were compared. The first loading involved a 50kg bag attached to either end of the rope. This was repeated for all three rope types and then the tests were replicated with 100kg of weight on either end of the rope. Therefore there were two different scenarios with total loadings in the rope of 100kg and 200kg.

The testing was done at a wrap angle of 90 degrees and on the same log to keep the majority of the parameters the same.

3.4.3 Log Condition

During Cable-Assist operations in the field, wire ropes are run along the outside of the trees. This will very quickly rip the bark off a tree and rub against the cambium layer below the bark. The logs used in the testing had been debarked by a processing head and therefore the wire ropes were run over the cambium layer for the majority of tests.

A rasp was used to rough up the surface to expose the fibres to see if this resulted in any difference to the estimated coefficient of friction. The wire ropes came pre-greased and the more fibrous texture of this area absorbed the grease more than the outer layer. To ensure this didn't skew results, the rope was moved side to side to a clean patch. The grease was filed off after each test. This grease can be seen in Figure 13 below.



Figure 12: Example of grease rubbing off the wire rope onto the fresh cambium layer

The area that had been roughed up by the processing head that can be seen in Figure 13 did not affect the testing as the cable exits the log before touching this area.

As a wire-rope wraps around a tree it is likely that it will cut into the tree. This was replicated on the main log by using a chainsaw to cut a groove into the log. This groove was U shaped and roughly as deep as the 13mm swaged cable. The cable sat flush in the groove and rubbed on all sides of the groove as it would do if the cable had cut the groove itself. The groove is shown in Figure 14 below.



Figure 13: Cable running through groove cut into log by chainsaw to mimic the cut done by the cable itself in the field

3.4.4 Log Diameter

The two logs were both cut flat on one edge to allow them to be attached to the piece of ply. The diameter of each log was measured and the circumference calculated from this value.

Table 2: Diameter and Circumference for the test logs

	Diameter (cm)	Circumference (cm)
Log A	32	100.5
Log B	39	122.5

All three ropes were tested at both a 45 degree wrap angle and a 90 degree wrap angle with 50kg load on either end of the rope (100kg tension in the rope).

4. RESULTS

The results of the tests explained above are outlined below. The coefficients of friction are calculated using the capstan equation:

$$T_2 = T_1 e^{\mu\theta}$$

T_1, T_2 and Θ are all measured during the tests so it is possible to rearrange this equation for μ :

$$\mu = \frac{\ln\left(\frac{T_2}{T_1}\right)}{\theta}$$

Overall there were 19 different test set-ups, each with a different parameter to test. Therefore a comparison for each parameter could be made with respect to the coefficient of friction and the parameter's effect on the coefficient of friction could be investigated. Table 3 outlines the 19 different tests and provides a breakdown of what parameters were tested in each.

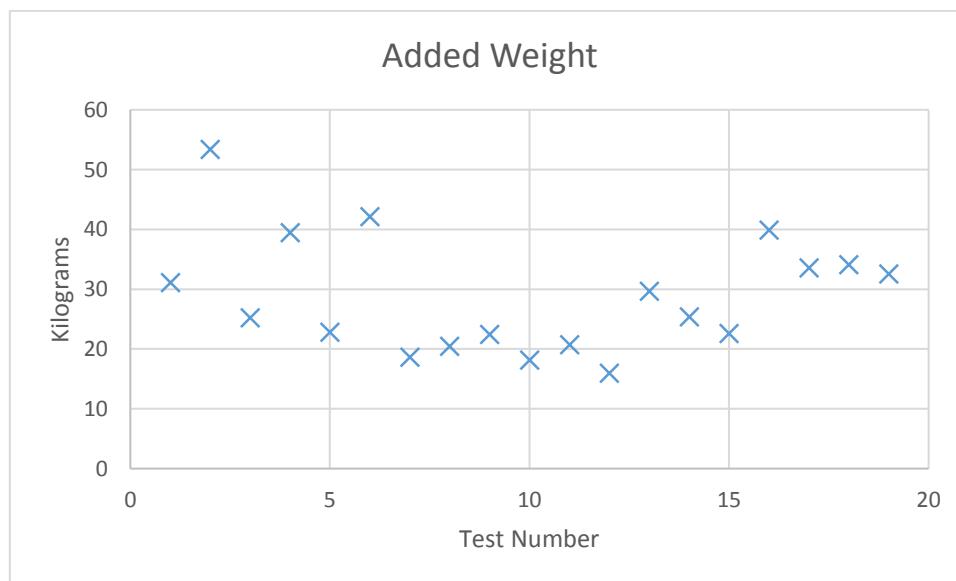
Table 3: Outline of the different tests performed to look at the different parameters affecting the coefficient of friction

Test	Rope	Control (kg)	Diameter	Angle
1	1	50	a	90
2	1	100	a	90
3	2	50	a	90
4	2	100	a	90
5	3	50	a	90
6	3	100	a	90
7	1	50	a	45
8	2	50	a	45
9	3	50	a	45
10	1	50	b	45
11	2	50	b	45
12	3	50	b	45
13	1	50	b	90
14	2	50	b	90
15	3	50	b	90
16	1	50	Groove	90
17	2	50	Groove	90
18	1	50	Cambium	90
19	2	50	Cambium	90

The raw data can be seen in Table 4 below. For each of the 19 tests the average of the measured added weight for each trial has been calculated. This has also been plotted in Figure 15. The raw data for every trial can be seen in Appendix C.

Table 4: Averaged raw results for added weight

Number	Rope	Control (kg)	Diameter	Angle	Added Weight
1	1	50	a	90	31.08
2	1	100	a	90	53.37
3	2	50	a	90	25.20
4	2	100	a	90	39.45
5	3	50	a	90	22.80
6	3	100	a	90	42.15
7	1	50	a	45	18.63
8	2	50	a	45	20.46
9	3	50	a	45	22.43
10	1	50	b	45	18.17
11	2	50	b	45	20.73
12	3	50	b	45	15.93
13	1	50	b	90	29.65
14	2	50	b	90	25.37
15	3	50	b	90	22.58
16	1	50	Groove	90	39.88
17	2	50	Groove	90	33.57
18	1	50	Cambium	90	34.12
19	2	50	Cambium	90	32.55

**Figure 14:** Average weight added of the trials done for each different test

The above figure doesn't show any clear trends and therefore the results are broken down by each parameter in separate sections below.

4.1 Rope Type

At least 3 trials were conducted per test set and the coefficient of friction was calculated for each trial. The average of these results was then calculated and recorded as the coefficient of friction for that particular test with those parameters. These values are sorted by rope type in Table 5 below:

Table 5: Breakdown of calculated coefficient of friction by rope type

Average Coefficient	Rope Type		
Test Number	1	2	3
1	0.308		
2	0.272		
3		0.260	
4		0.212	
5			0.239
6			0.224
7	0.403		
8		0.437	
9			0.472
10	0.395		
11		0.442	
12			0.352
13	0.296		
14		0.261	
15			0.237
16	0.373		
17		0.327	
18	0.331		
19		0.319	
Average	0.340	0.322	0.305

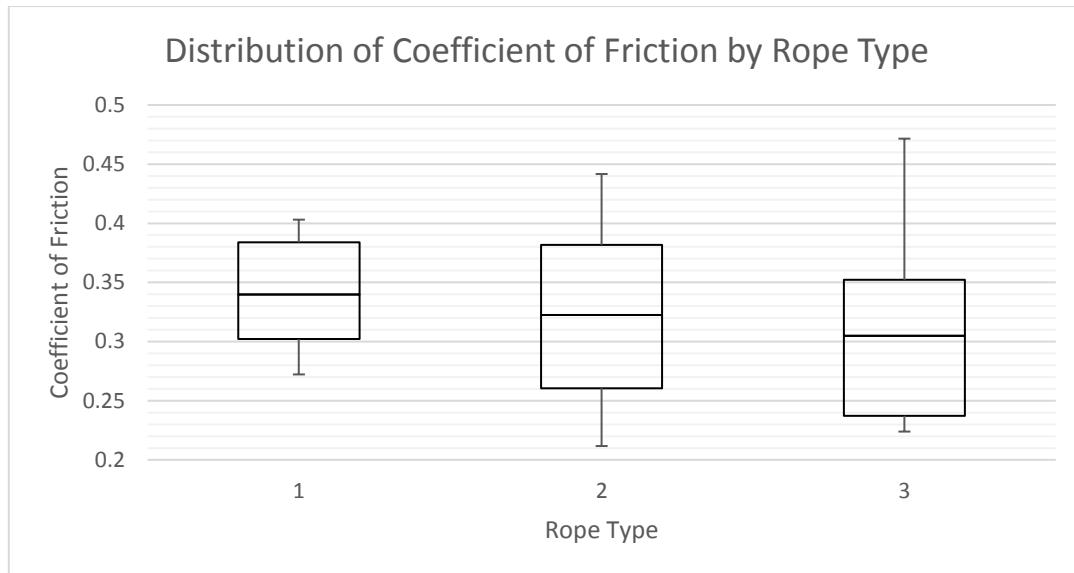


Figure 15: Box and Whisker Plot of the Coefficients of Friction by Rope Type. This plot illustrates the Maximum, 75th Quartile, Average, 25th Quartile and the Minimum values for each data set.

The mean coefficient of friction is the highest for the swaged rope. As expected the smallest rope has the smallest coefficient of friction as it has the least contact area between the two materials.

4.2 Wrap Angle

The wrap angle was compared with a loading of 50 kilograms on either end of the rope and tests were completed on both log A and log B. To compare between wrap angles, the tests that were done with 100kg loading on each end of the rope with a 90 degree wrap angle and the tests that were done with different log conditions have been removed. This is done so that the only parameter compared is the wrap angle on the two different logs.

Table 6: Wrap angle comparison of all ropes on both logs with 50kg loading on each end of the rope.

Average Coefficient	Wrap Angle	
Test Number	45	90
1		0.308
3		0.260
5		0.239
7	0.403	
8	0.437	
9	0.472	
10	0.395	
11	0.442	
12	0.352	
13		0.296
14		0.261
15		0.237
Average	0.417	0.267

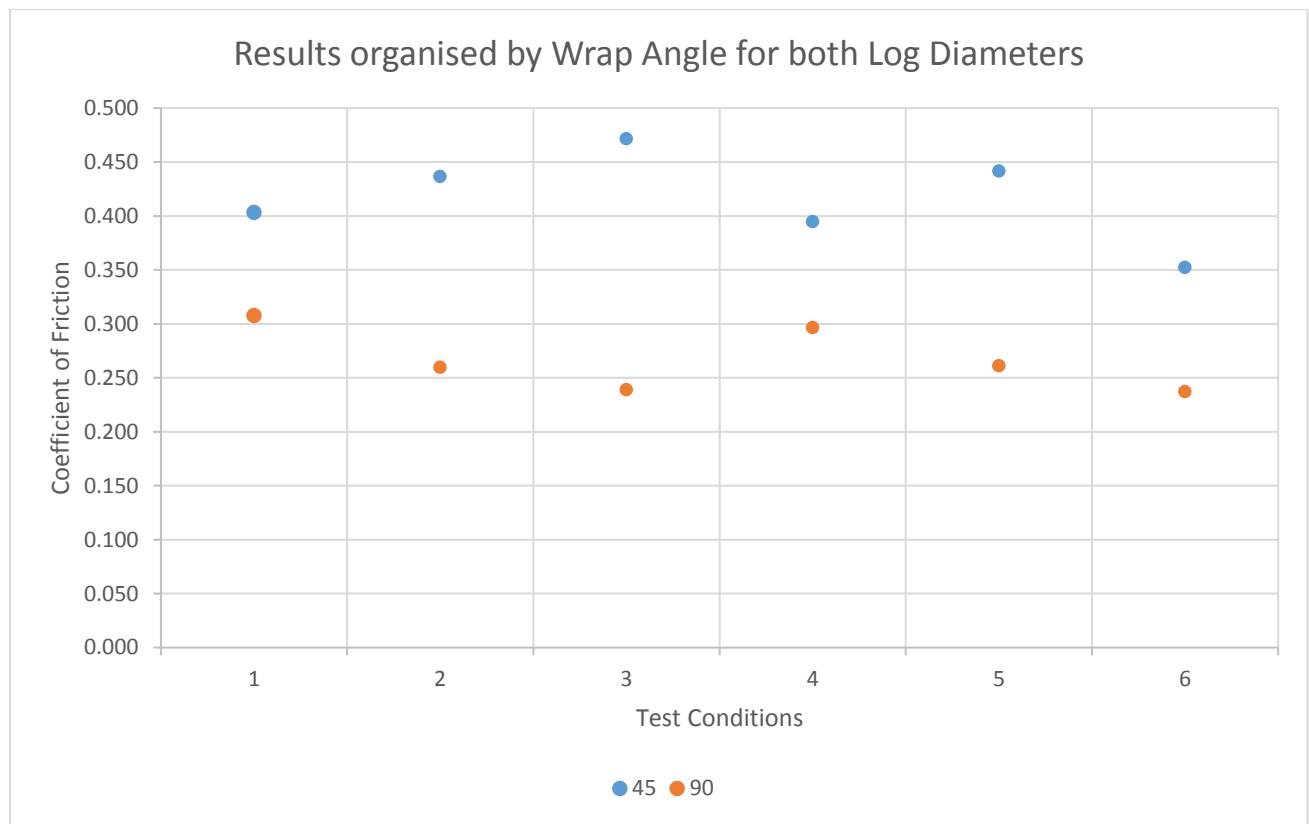


Figure 16: A comparison of the coefficient of friction with a wrap angle of 45 degrees and 90 degrees with two different logs. X-axis values 1, 2 and 3 are Log A and values 4, 5 and 6 are log B.

4.3 Rope Loading

Investigating the difference in loading involved doubling the weight applied to the rope when run at a 90 degree wrap angle over log A. The following table outlines the average results from the trials for the three different ropes.

Table 7: Difference in coefficient of friction due to the loading of the rope

Average Coefficient	Rope Loading (kg)	
Test Number	50	100
1	0.308	
2		0.272
3	0.260	
4		0.212
5	0.239	
6		0.224
Average	0.269	0.236

The 50kg column refers to a loading of 50kg at either end of the rope, so the total loading of the rope is 100kg before extra weight is added. The 100kg column applies to two 100kg weights at either end, resulting in a 200kg loading in the rope. Tests 1 and 2 look at the 13mm swaged rope, tests 3 and 4 look at the 13mm non-swaged rope and tests 5 and 6 look at the 9mm non-swaged rope.

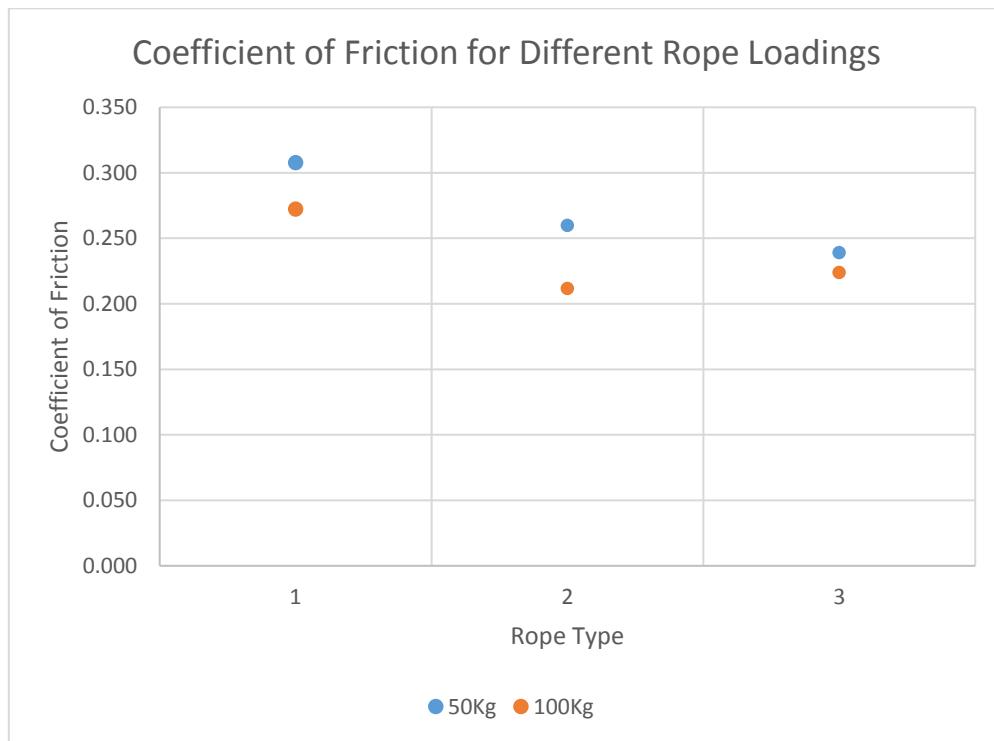


Figure 17: A comparison of the coefficient of friction between two different loadings categorised by rope type

As seen in Figure 18 all three ropes have a lower coefficient of friction for the 100kg tests than the 50kg tests.

4.4 Log Condition

Table 8 outlines the calculated coefficient of friction for different log conditions. The 'Diameter A' numbers are the results from running the rope over the outside of the log on the standard exterior surface. The 'Cambium' results involved running the rope over freshly exposed and roughed up cambium layer as seen in Figure 13 (Section 3.4.3). The 'Groove' numbers are the results from the tests that ran the ropes through the groove cut to fit the two 13mm ropes.

Table 8: Effect that log condition has on the coefficient of friction

Average Coefficient		Rope Type		
Diameter A	Test#	1	2	Average
	1	0.308		0.308
	4	0.272		0.272
	7		0.260	0.260
	10		0.212	0.212
Average		0.290	0.236	0.263
Cambium	52	0.331		0.331
	55		0.319	0.319
	Average			0.325
Groove	46	0.373		0.373
	49		0.327	0.327
	Average			0.350
Average		0.321	0.279	0.300

The condition of the log influences the friction between the two materials as we can see in the above table. Only ropes 1 and 2- the 13mm swaged and non-swaged ropes- were compared across all three mediums as the 9mm non-swaged rope was too small to fit snugly in the groove. It is clear that the tests run through the groove result in the highest average coefficient of friction and the rough cambium layer also causes more friction than the standard outer layer. This means more weight needed to be added to cause the system to slip. The groove caused an increase in the coefficient of friction of 28% while on the non-swaged rope there is an increase of 38%.

4.5 Log Diameter

Log A has a 32 centimetre diameter and log B has a 39 centimetre diameter. This is approximately a 22% increase in diameter resulting in a 22.5 centimetre increase in circumference. Table 9 outlines the results from the tests on both these logs.

Table 9: Looking at the influence that log diameter has on the coefficient of friction. Results for both 45 and 90 degree wrap angles on both logs.

Average Coefficient	Log Diameter					
	Angle: 45			Angle: 90		
Rope	A	B	Difference	A	B	Difference
1	0.403	0.395	0.008	0.308	0.296	0.011
2	0.437	0.442	0.005	0.260	0.261	0.001
3	0.472	0.352	0.119	0.239	0.237	0.002

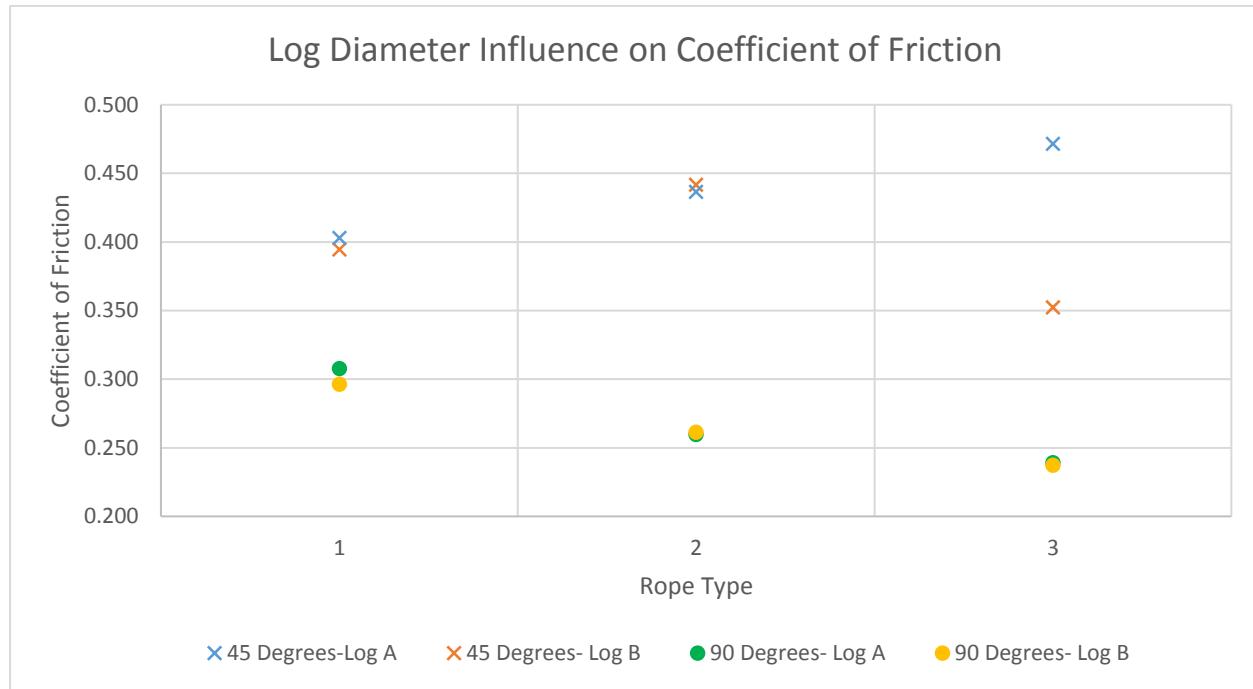


Figure 18: Investigating the influence that log diameter has on the coefficient of friction between wire ropes and external log surfaces

The difference between the logs is minimal, resulting in an average absolute difference between the coefficient of friction for each pair of tests of 7%. This includes what appears to be a large outlier for the 45 degree test using the 9mm swaged rope (Rope 3) which has a much larger difference than the other tests. If this test is removed then the average difference is 1.7%. Calculations for this are in Appendix B.

5. DISCUSSION

5.1 Theory and Experimentation

Using the capstan equation to estimate a coefficient of friction is not a new concept and has been used a couple of times before in different industries. It is then fair to say that the method used in this project is valid for the purposes of improving our knowledge around wrapping wire ropes around trees. It is important to note that these tests can only be used to help understand the

mechanics of the rope-tree relationship in a Cable-Assist system. The capstan equation has its own limitations and furthermore can only provide an estimate for a coefficient of friction in these tests. One of these limitations is that the capstan equation assumes the capstan to be perfectly circular and a tree is generally never perfectly circular therefore further research is paramount. Scaling up the tensions and stresses on the rope to the magnitude used within the field would provide a more realistic estimation of the coefficient of friction for cable-assist systems. It is possible that the coefficient of friction will change with high loadings as can be seen by the difference in results testing at the two different loadings in this report.

An important limitation of the Capstan equation is the fact that it doesn't take into consideration the force applied by the rope on itself when a wrap angle of larger than 360 degrees occurs. Fulton (2005) investigated this in a paper written about sailing winches where this is a common occurrence and found that there is some difference between this scenario and a wrap angle of less than 360 degrees. This particular case is extremely unlikely to occur in a Cable-Assist situation, as the maximum wrap angle would rarely even reach 180 degrees as this would mean the machine is travelling back the way it came from, either uphill or across the slope while keeping the cable wrapped around the tree.

The testing apparatus ended up being a very efficient and accurate set up. The largest hindrance was the inability to load the system up to high weights however for the lower weights that were measured, it worked very well. Accuracy of the results is relatively consistent as the rope angle was measured each time using a digital level that was accurate to ± 0.1 degree. The scales used to weigh the sand and extra weights were accurate to ± 0.05 kg. Therefore the measurement involved in the testing was quite accurate and care was taken to avoid spilling sand and ensure no extra sand was added to the weights by watching the rope for movement after every scoop.

At the start of the test period, both directions of movement were tested with regards to rope movement over the log. This was done to ensure that there was no difference in the results due to the direction the rope travelled with our testing apparatus. There was no difference between the two directions and therefore every measured test was done the same way, with the rope moving towards the crane end.

5.2 Result Analysis

From the results it appears that the friction coefficient comes down to the contact area between the tree and rope. This appears to disagree with Attaway (1999) that the friction coefficient does not depend on rope size, however the difference is evident in the comparison between the three ropes as it appears that the flatter contact patch of the 13mm swaged rope could be the reason for a

higher coefficient of friction for both the 50kg and 100kg tests. The higher ribbing of the non-swaged rope when it is not being compressed provided a smaller contact area as the rope appeared to touch on each strand. This meant that there were many tiny little contact patches between the rope and the log. This may be the reason for the 5% difference in values. This is actually different to my original hypothesis about the rope types as I believed the rough profile of the non-swaged would provide more resistance but after testing this was proved to not be the case. This may be due to the fact that the loading is not high enough for the rope to cut into the log itself, which would be an area for further research. As expected, the smaller rope has a smaller coefficient of friction due to the smaller contact area.

The results of the testing were actually slightly higher than expected as Kimbell (1982) stated a coefficient of friction of 0.1768 however Kane (2007) found the co-efficient of friction for synthetic arborist ropes on steel cambium saver rings to be higher with an average coefficient of friction of 0.24. When considering the materials used in this experiment, the averages hovering around the 0.3 mark seem reasonable due to the rougher nature of wood acting as a capstan than steel.

When investigating the notch that was cut into the log, it is important to note that the coefficient of friction was higher. This is likely due to the higher contact area however it is important to note that Kimbell (1982) investigated wrapping a rope around a tree in a V-notch. There was an adjustment to the capstan equation which involved a β term where β was the notch angle. This only applied to a V-notch and there was no reputable equation found for a U-notch that wasn't regarding wrapping rope on a pulley. The cut by the chainsaw closely resembled a U-notch and further investigation into at U notch relationship could then be applied to the raw data found in Appendix C if a suitable replacement equation was determined.

5.3 Further Research

This research project clearly shows that the relationship between a wire rope and a log or tree is complicated. Further research into the effect of wire rope type on the log is important. Looking at cables with a larger diameter or the same diameter as the ropes used in the field would be the logical next step. This would require much larger forces and stronger gear and might need to be tested in the field to more closely represent a real life situation as the cables themselves will be much harder to bend around a log. Investigating different rope types, including rope lay and rope structure could also be an area of further research.

Another area of interest could be determining how long it takes for a rope to cut into a tree, as the results show that the ropes in the grooves that were cut returned a higher coefficient of friction. The increase in coefficient of friction could cause issues in the field as the difference in tensions when

wrapped around the tree within a groove could affect winch operation or increase the likelihood of the tensions within the wire rope breaching the safe working load. As discussed in section 5.2, further investigation into a U notch would be beneficial and to also investigate the general shape of the notch that the rope cuts through repeated back and forth motion across the surface of the tree. As this will cut in with the shape of the rope itself, it may have even more contact area than that of a U-notch or V-notch resulting in larger coefficient of frictions and thus larger tension differences.

A final area of further research could be the investigation into much larger differences in diameter. The capstan equation is independent of the diameter of the object that the rope is wrapping around. While this project shows that an increase of 22% in diameter appeared to make very little difference and reinforces this fact, there is no evidence that doubling the diameter will yield the same results as the much larger contact area between the larger log and the wire rope could influence the results.

6. CONCLUSION

Cable-Assist is a relatively new technology which has introduced some new practices to the forestry industry such as wrapping moving lines around trees. Doing so has introduced the need to understand the interaction between the ropes and the trees. Exploring what happens to the tension in these lines on either side of the tree is a big part of this problem. The intention of this project was to investigate the interaction between a wire rope and a tree. A testing rig was fabricated in the forestry workshop which was used to repeat multiple tests quickly and accurately. Two logs with different diameters were obtained from a forest which had been felled relatively recently and these were de-barked and tested with three wire ropes that were obtained from Bridon's to study an array of parameters with respect to the friction coefficient between these two materials.

A total of 69 tests were conducted to return an overall coefficient of friction average of 0.342 ± 0.009 . This average included all three rope types from which individual averages could be calculated. Rope 1 was a swaged 13mm rope that had an average coefficient of friction of 0.340 ± 0.019 . Rope 2 was a conventional non-swaged 13mm rope with an average coefficient of friction of 0.322 ± 0.034 . Rope 3 was a 9mm conventional non-swaged rope and returned a coefficient of friction of 0.304 ± 0.048 . The larger error found in the individual rope tests come from a lower number of respective tests. An important result concluded from the tests was that running the ropes through a notch directly affected the coefficient of friction, increasing it by 28-38% depending on the rope. A large difference like this could directly relate to issues on a real system if tension spikes are already reaching close to safe working loads.

As expected, contact area was determined to be the major contributor to the coefficient of friction however the 22% increase in diameter affected the coefficient of friction by only 1.7% even though the area the rope would have been in contact with the wood would have been larger. This reinforces the independent nature of the Capstan Equation with respect to capstan diameter, at least with smaller increases in diameter. Further investigation into large diameter increases over 50% would be beneficial for backing up this data.

The largest limitation of this study was the inability to replicate in-situ tensions and working loads. Therefore a full size 7/8" or 1 1/8" cable that is used in a Cable-Assist system couldn't be tested. This is a good area of potential further research that could be done with tension monitors applied to a working system in the field.

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8. ACKNOWLEDGEMENTS

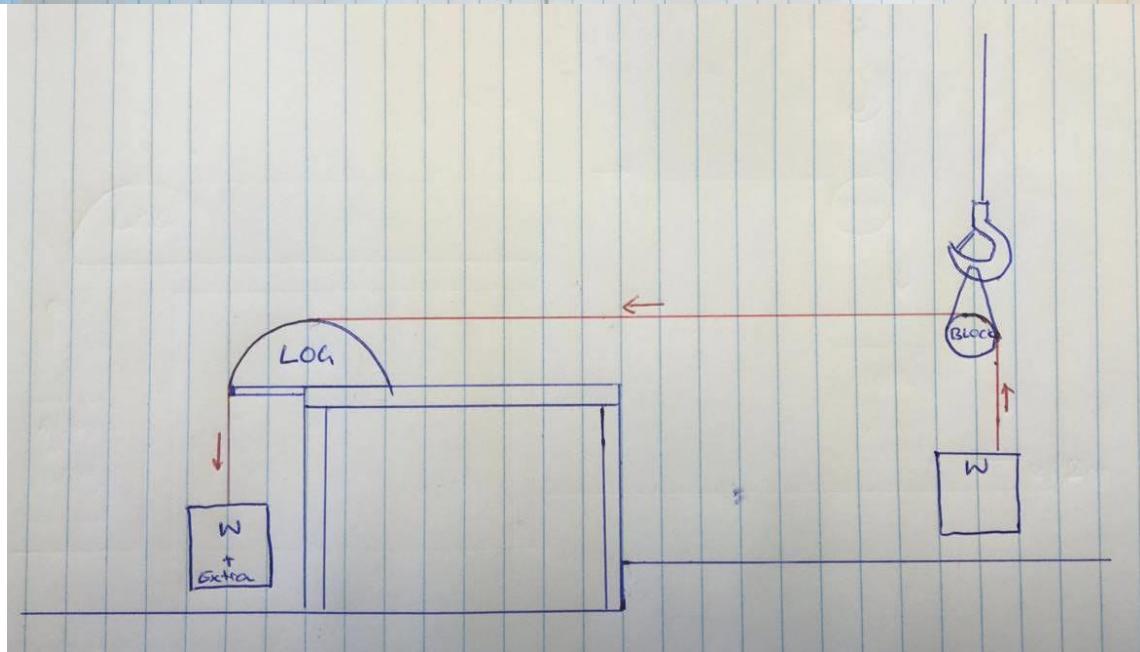
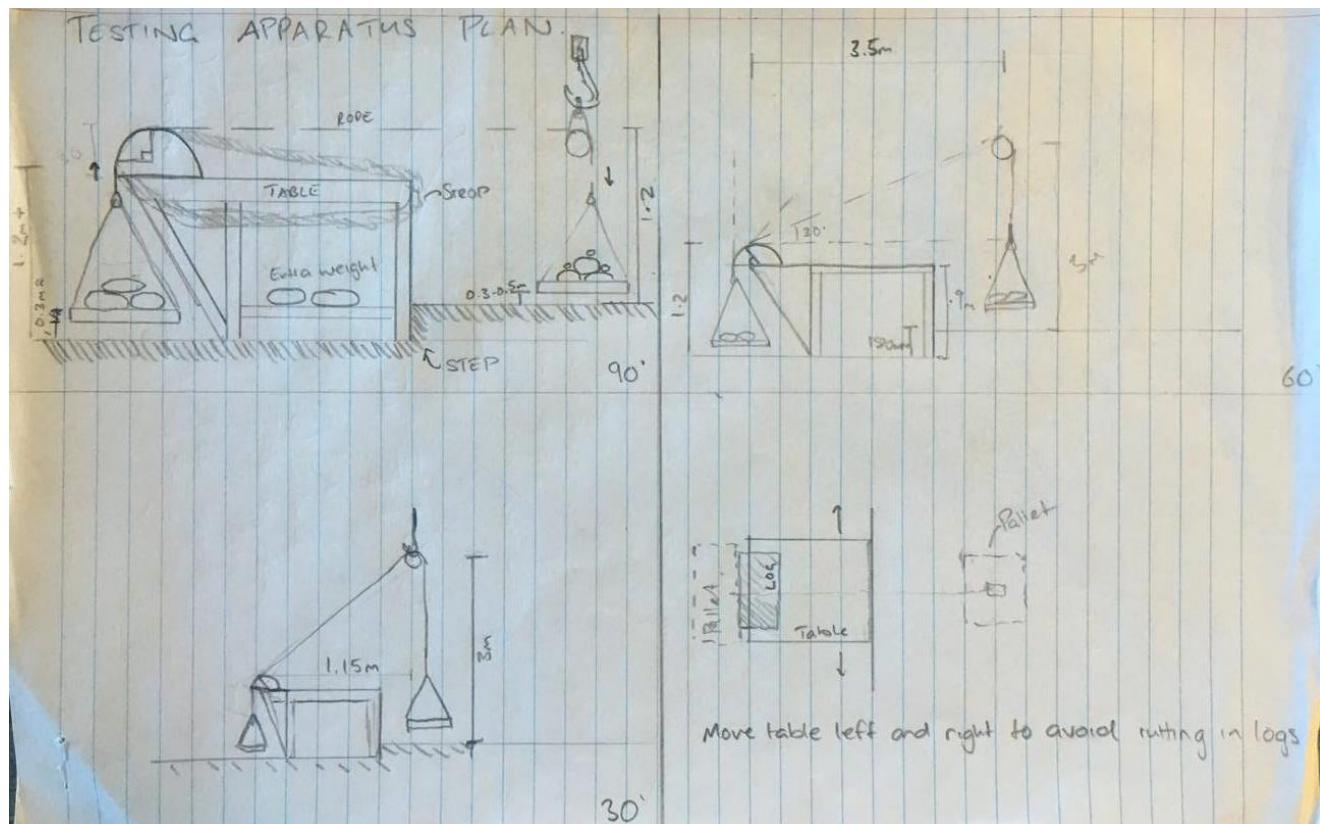
I would like to express my thanks to Rien Visser for funding and guidance throughout the project.

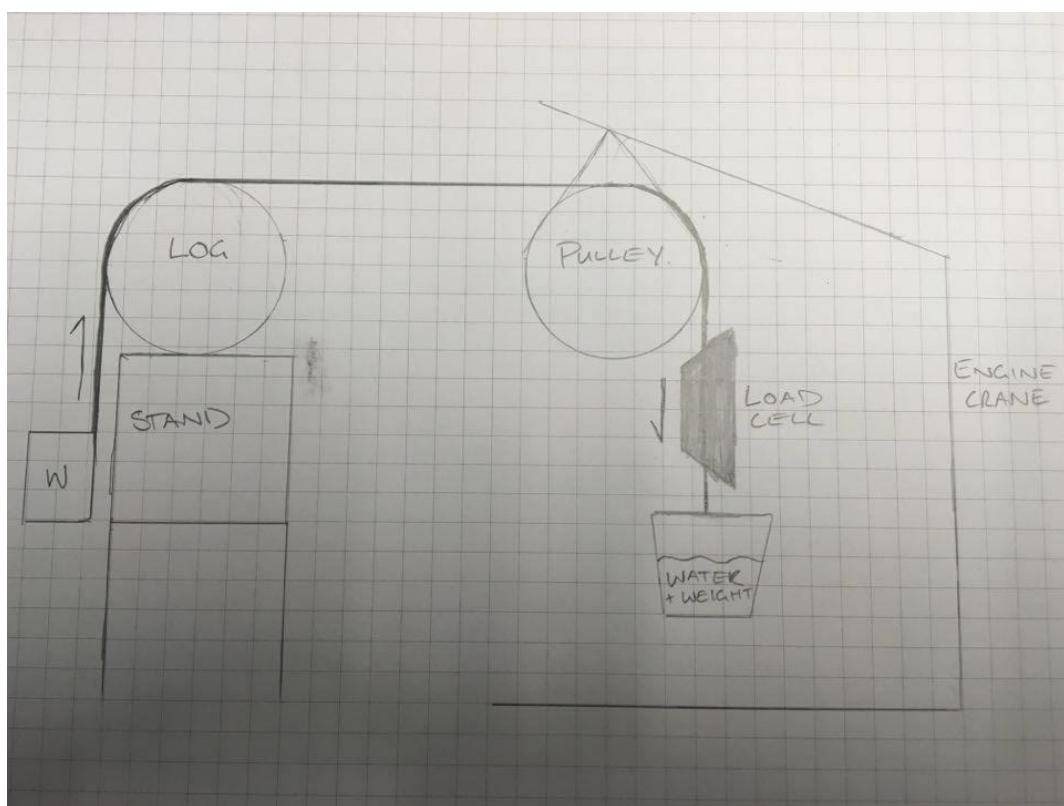
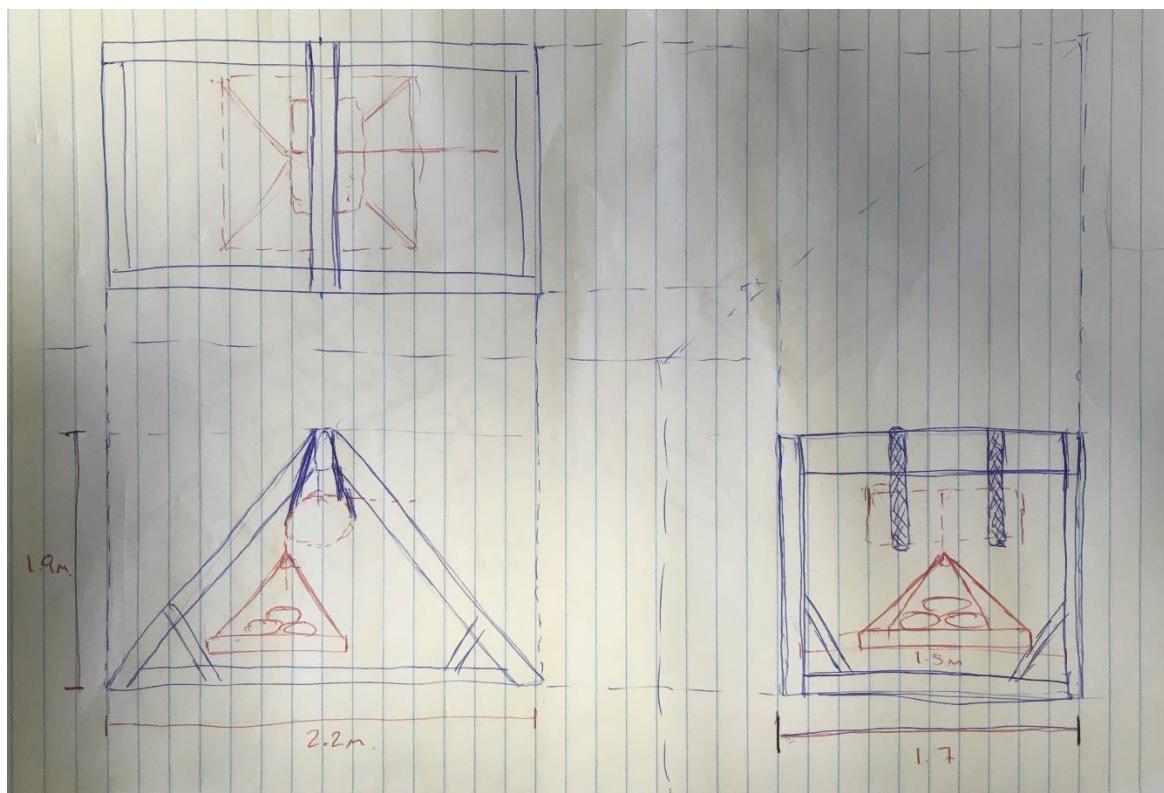
I would also like to thank Hunter Harrill for advice and guidance throughout this project.

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9. APPENDICES

APPENDIX A -Initial design sketches for testing apparatus





APPENDIX B- Calculations for percent difference in log diameter results section.

Average Coefficient	Diameter							
Angle	45				90			
Rope	a	b	Difference	Percent Difference	a	b	Difference	Percent Difference
1	0.403	0.395	0.008	2.15	0.308	0.296	0.011	3.84
2	0.437	0.442	0.005	1.16	0.260	0.261	0.001	0.55
3	0.472	0.352	0.119	33.89	0.239	0.237	0.002	0.78
Average Percent Difference (%) = 7.1								
Without Outlier (%) = 1.7								

APPENDIX C- Raw Data

Test #	Rope	Control (kg)	Diameter	Angle	Measured Weight	Applied Tension	Total Tension in Rope	CoF
1	1	50	a	90	31.75	81.75	131.75	0.313
2	1	50	a	90	30.6	80.6	130.6	0.304
3	1	50	a	90	30.9	80.9	130.9	0.306
4	1	100	a	90	50.7	150.7	250.7	0.261
5	1	100	a	90	55.2	155.2	255.2	0.280
6	1	100	a	90	54.2	154.2	254.2	0.276
7	2	50	a	90	26.1	76.1	126.1	0.267
8	2	50	a	90	24.6	74.6	124.6	0.255
9	2	50	a	90	24.9	74.9	124.9	0.257
10	2	100	a	90	39.9	139.9	239.9	0.214
11	2	100	a	90	40.5	140.5	240.5	0.216
12	2	100	a	90	37.95	137.95	237.95	0.205
13	3	50	a	90	24.45	74.45	124.45	0.253
14	3	50	a	90	22.3	72.3	122.3	0.235
15	3	50	a	90	21.65	71.65	121.65	0.229
16	3	100	a	90	41.9	141.9	241.9	0.223
17	3	100	a	90	42.55	142.55	242.55	0.226
18	3	100	a	90	42	142	242	0.223
19	1	50	a	45	18.55	68.55	118.55	0.402
20	1	50	a	45	17.75	67.75	117.75	0.387
21	1	50	a	45	18.5	68.5	118.5	0.401
21a	1	50	a	45	17.5	67.5	117.5	0.382
21b	1	50	a	45	17.85	67.85	117.85	0.389
21c	1	50	a	45	17.95	67.95	117.95	0.391
21d	1	50	a	45	19.9	69.9	119.9	0.427

21e	1	50	a	45	20.25	70.25	120.25	0.433
21f	1	50	a	45	19.4	69.4	119.4	0.417
22	2	50	a	45	22.15	72.15	122.15	0.467
23	2	50	a	45	20.1	70.1	120.1	0.430
24	2	50	a	45	20.55	70.55	120.55	0.438
24a	2	50	a	45	20.8	70.8	120.8	0.443
24b	2	50	a	45	19.55	69.55	119.55	0.420
24c	2	50	a	45	19.6	69.6	119.6	0.421
25	3	50	a	45	21.4	71.4	121.4	0.454
26	3	50	a	45	24.8	74.8	124.8	0.513
27	3	50	a	45	23.15	73.15	123.15	0.484
27a	3	50	a	45	20.6	70.6	120.6	0.439
27b	3	50	a	45	22.2	72.2	122.2	0.468
27c	3	50	a	45	22.4	72.4	122.4	0.471
28	1	50	b	45	18.4	68.4	118.4	0.399
29	1	50	b	45	18.3	68.3	118.3	0.397
30	1	50	b	45	17.8	67.8	117.8	0.388
31	2	50	b	45	20.3	70.3	120.3	0.434
32	2	50	b	45	20.8	70.8	120.8	0.443
33	2	50	b	45	21.1	71.1	121.1	0.448
34	3	50	b	45	15.95	65.95	115.95	0.353
35	3	50	b	45	15.8	65.8	115.8	0.350
36	3	50	b	45	16.05	66.05	116.05	0.354
37	1	50	b	90	30.75	80.75	130.75	0.305
38	1	50	b	90	29.6	79.6	129.6	0.296
39	1	50	b	90	28.6	78.6	128.6	0.288
40	2	50	b	90	24.85	74.85	124.85	0.257
41	2	50	b	90	25.8	75.8	125.8	0.265
42	2	50	b	90	25.45	75.45	125.45	0.262
43	3	50	b	90	23.5	73.5	123.5	0.245
44	3	50	b	90	22.4	72.4	122.4	0.236
45	3	50	b	90	21.85	71.85	121.85	0.231
46	1	50	Groove	90	40.45	90.45	140.45	0.377
47	1	50	Groove	90	38.25	88.25	138.25	0.362
48	1	50	Groove	90	40.95	90.95	140.95	0.381
49	2	50	Groove	90	34.25	84.25	134.25	0.332
50	2	50	Groove	90	32.5	82.5	132.5	0.319
51	2	50	Groove	90	33.95	83.95	133.95	0.330
52	1	50	Cambium	90	33.95	83.95	133.95	0.330
53	1	50	Cambium	90	33.55	83.55	133.55	0.327
54	1	50	Cambium	90	34.85	84.85	134.85	0.337
55	2	50	Cambium	90	33.35	83.35	133.35	0.325
56	2	50	Cambium	90	33.95	83.95	133.95	0.330
57	2	50	Cambium	90	30.35	80.35	130.35	0.302