Capacity of Second-Growth Douglas-fir and Western Hemlock Stump Anchors for Cable Logging[1]

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ABSTRACT

The use of small instead of large stumps for cable logging anchors will usually result in applied loads approaching the load capacity of the anchors more closely. The use of small stump anchors is then contingent on better means of assessing their capacity. The results of field load tests of Douglas-fir and western hemlock stump anchors are reported. Ultimate loads were modeled as power functions of DBH. In addition, the relation between load and movement relationships for the stumps are modeled using a hyperbolic function that also provides an estimate of ultimate load. Practical use of the model equations requires knowledge of failure statistics and the acceptance of a probabilistic anchor capacity. Probability is applied to the re-rigging required when an anchor fails to perform adequately and to total pull-out failure.

Keywords: *Stump-anchors, cable-logging, failure, rigging, second-growth.*

INTRODUCTION

Stump anchors are usually the most convenient and economic means of stabilizing cable-logging systems (Figure 1). Loggers using cable systems have extensive experience with the large stump anchors typically available for harvesting old-growth timber but far less experience with smaller second-growth stumps. However, smaller stumps will often be the only ones available adjacent to residual old-growth harvest units or in second-growth stands. Selection of stumps that have sufficient capacity to resist applied loads is critical to safe and economic operation of cable logging systems. Failure of an anchor can result in equipment damage and even injury or loss of life to logging crew members. Further, if a stump anchor pulls out of the ground during yarding, a production delay will result while a new stump is rigged even if no equipment damage or injury occurs.

We expect that safe use of second-growth stump anchors will require that existing experience and judgement be supplemented with specific data on load capacity of the anchors. This paper presents the results of a series of static-load tests conducted on second-growth Douglas-fir and western hemlock stumps, probabilistic models of the capacity of the stumps tested, and a discussion of the practical use of the capacity relationships. The capacity relationships presented are specific to the field test sites, but they do constitute a framework into which addition test results obtained from a broader range in field conditions can be incorporated.

STUDY PROCEDURES

Site-specific factors believed to influence the pull-out resistance of stumps have been reviewed by Pyles and Stoupa [4]; these include species, diameter, age, soil depth, soil type, soil moisture, prevailing wind conditions, ground slope, stand density, and tree form. In addition, loading direction [3] and type of load (i.e. static or dynamic) may be important [4]. Although an adequately replicated testing program including load tests throughout the range of each of the listed site-specific variables would be desirable, it would clearly be cost-prohibitive. Therefore, we elected in this study to eliminate most variation other than stump diameter. This was done by limiting the field testing to stumps from three sites (one Douglas-fir site and two western hemlock sites), conducting the tests over a short period (4 to 6 weeks) to limit temporal variation in soil moisture at

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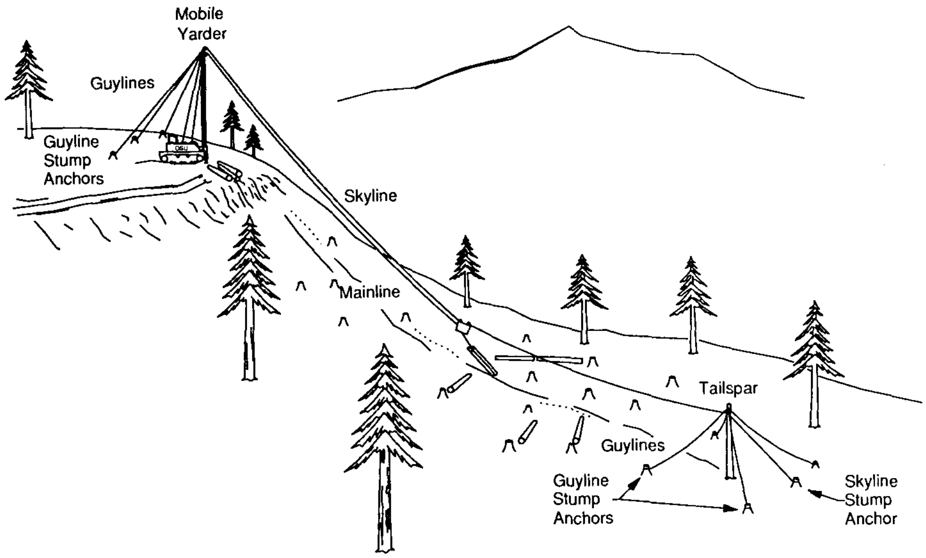

Figure 1. A typical skyline logging system. Stumps are used for guyline anchors and for the skyline anchor.

each site, and applying static loads parallel to the ground at the stump location.

Test Sites

Static-load tests were conducted on 18 Douglas-fir stumps located northwest of Corvallis, Oregon in Oregon State University's Paul Dunn Forest [4]. The naturally regenerated timber stand was primarily Douglas-fir, with some white fir, and contained a large hardwood component, primarily bigleaf maple. The tests were conducted during the summer in 1983. Soil moisture values at the time of testing (Table 1) approached field capacity—35% to 40% (H.A. Froehlich, Oregon State University, personal communication, 1987), but the higher soil moisture likely to exist during periods of heavy rainfall was probably not reflected.

Two field sites on the Olympic Peninsula, Washington, were selected for static testing of the hemlock stumps — near Quinault and near Forks. The two western hemlock sites were selected to provide a greater range in stump diameter than could be found within reach of the test equipment at a single site. The Quinault site was classified as a bottomland wet site with ground slope less than 10%. The stand was approximately 80% western hemlock and 20% silver fir. The Forks site was an upper slope site with an average ground slope of about 30%; it was nearly 100% western hemlock. The load tests were conducted in the summer of 1985. The western side of the Olympic peninsula experiences relatively wet summers; consequently we assumed that soil moisture (Table 1) approached field capacity.

It is common in coastal hemlock stands for natural regeneration to include many trees that germinate on the top of old stumps or windfall logs as well as those that germinate on the forest floor. The trees that germinate on top of stumps or logs are usually termed stilt-rooted because the roots bifurcate above the groundline and often extend vertically to the ground before radiating out in the normal manner. Stilt-rooting can be considered to range from zero for normally rooted stumps to as much as 0.6 to 0.9 m [2 to 3 feet] at the Quinault and Forks sites. Practical considerations including the need to select stumps within reach of the truck mounted winch used for pulling, the need to re-use reaction trees (Figure 2) so as to minimize stand damage, and the need to hold costly rigging time to a minimum precluded taking a random sample of the distribution of stilt-rooted stumps; instead, we took stratified sample. To establish the range of likely stump behavior and a conservative estimate of average behavior, we sampled the extremes of the range in stumps on the basis of visually observable rooting conditions. We intended to select roughly equal numbers of normal stumps rooted directly in soil and extremely stilt-rooted stumps. At the two hemlock sites, extreme stilt-rooting was considered to be 0.3 to 0.6 m [1 to 2 feet] of root above the groundline for any stump that

Table 1. Tests and Conditions at the three test sites.

Characteristic	Dunn Forest, OR	Quinault, WA	Forks, WA
Stumps tested:			
Normal	18	9	5
Stilt-Rooted	-	4	6
Timber stand:			
Species	Douglas-fir	Western hemlock	Western hemlock
Age, yr.	42	50	50
Avg. DBH, cm	30.5 [12 in.]	53.3 [21 in.]	53.3 [21 in.]
Avg. height, m	26.5 [87 ft]	38.1 [125 ft]	39.6 [130 ft]
Soil profile	7.5-10 cm [3-4 in.] organic litter; 30 cm [12 in.] sandy silt (major rooting zone); highly plastic silt (little root penetration).	7.5-10 cm [3-4 in.] organic litter; 15-46 cm [6-18 in.] gravelly silt loam (major rooting zone); plastic clay (little root penetration).	7.5-10 cm [3-4 in.] organic litter; 46-91 cm [18-36 in.] sandy, gravelly clay (major rooting zone) grading to bedrock at deeper levels.
Rooting Zone Soil Properties:			
Soil moisture, %	20-40	40-70	45-85
Avg. Unconfined Compressive Strength*, kN/m^2		253 [5280 lb/ft^2] Std Dev = 57 [1200 lb/ft^2]	235 [4900 lb/ft^2] Std Dev = 19 [400 lb/ft^2]
Avg. ground slope, %	37	<10	30

* Determined with a pocket penetrometer.

might be considered for a cable-logging anchor. Our final sample was composed of 10 (~40%) stilt-rooted hemlock stumps, and 14 (~60%) stumps rooted directly in the soil.

Test Procedure

The general test procedure was to apply a series of loads to each stump at a rigging point 0.305 m [1 foot] from the groundline and record the stump movement resulting from each load. The load was applied parallel to the ground surface in the upslope direction in cases where there was a ground slope. Loading nearly parallel to ground slope occurs often with yarder guyline anchors when cable logging is done from ridge-top landings. However, numerous cases exist when there will be a large load component normal to the hillslope. These conditions will ultimately have to be studied.

Because of the high loads required to pull the larger stumps out of the ground, a block purchase system was used to gain a 14 to 1 mechanical advantage (Figure 2). In the Douglas-fir tests, the loads were held constant while readings of load and movement were taken manually. In the hemlock tests, the load was applied by a power-driven winch, and load and movement were determined electronically by a computer controlled data-acquisition system. The system allowed the load to be continuously increased at a slow rate while data were being recorded.

The applied load was measured with a 445 kN [100,000 lb] capacity electronic load cell installed between the block-purchase system and the stump (Figure 2). Stump movement was measured horizontally and vertically at three points on a frame attached to the top of the stump during the initial tests, and only in the horizontal direction at two points during the latter stages of the testing program. The three point measurements allowed computation of horizontal movement as well as rotational movement. Generally, horizontal movement was so small that it could not be reliably detected even at rotational movements as large as 3 to 5 degrees. Therefore, the three point measurement system was reduced to the two point system capable of detecting only rotational movement for the remainder of the testing.

The movement measuring system had a limited range of approximately 5 to 7.5 cm [2 to 3 inches] of stump movement at the rigging height. Typically at this range, the root system had been permanently deformed, although the ultimate load for the test stump had not been reached. For this reason, when the maximum recordable movement was attained, the movement measuring system was disconnected and the load tests were continued until there was

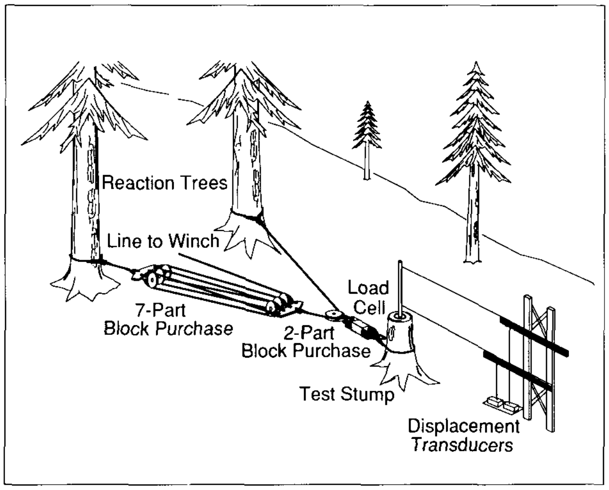

Figure 2. Rigging for stump-load tests.

complete stump failure, a procedure ensuring that the maximum load was recorded.

RESULTS

Preliminary tests showed that the primary stump movement was rotational in the vertical plane of the load. Rotational movement is a normalized movement that can be used to relate the behavior of one stump to that of another. However, it is not easily interpreted in terms of the behavior of a cable logging system. A far better measure of movement would be stump translation at the rigging height since this directly gives the movement of the end of the guyline or skyline if the stump were actually being used for a cable-logging anchor. For this reason, all stump movements were converted to horizontal movement at a 0.305 m [1-foot] rigging height by using similar triangle geometry (Figure 3).

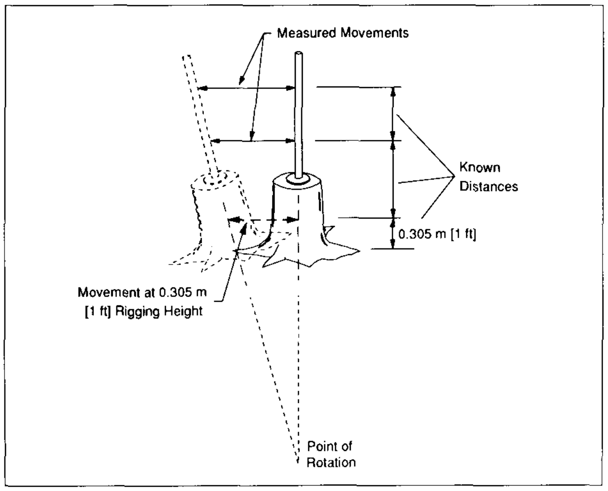

Figure 3. Geometry of stump movement used to obtain horizontal movement at the rigging height.

Preliminary tests also showed that stump anchors do not have a distinct yield point at which failure occurs. Movement of the stump increases gradually at first and then at an increasing rate as the applied load increases until an ultimate load is reached (Figure 4). If the ultimate load is maintained, the stump will quickly pull free of the ground. The absence of a distinct yield point in material behavior generally requires that capacity be defined in terms of an acceptable movement or system deformation [1]. For a stump anchor therefore, failure should be defined in terms of an acceptable stump movement.

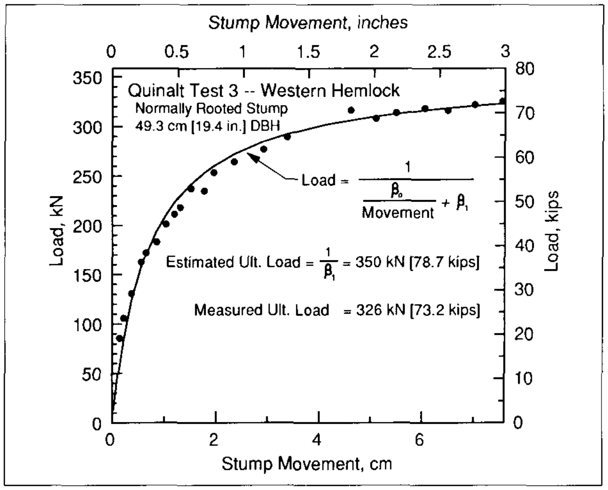

Figure 4. Typical load versus stump movement data.

Unfortunately, there are no established rules detailing acceptable movement of stump anchors. The limit of acceptable movement is normally a matter of judgement by the logger. It likely varies as a function of stump species, stump size, visual quality of the stump (tree), inferred soil conditions, and rigging configuration. For these reasons the stump anchor tests were analyzed for both the ultimate load and the load versus movement relationship. The analyses for ultimate load included tree diameter, soil moisture, and soil strength for the Quinault and Forks field sites. No strong correlations were found between soil moisture or soil strength and ultimate load for the three data sets [5]. However, the limited range in soil moisture and strength in these data sets should not be expected to produce strong correlations with ultimate load.

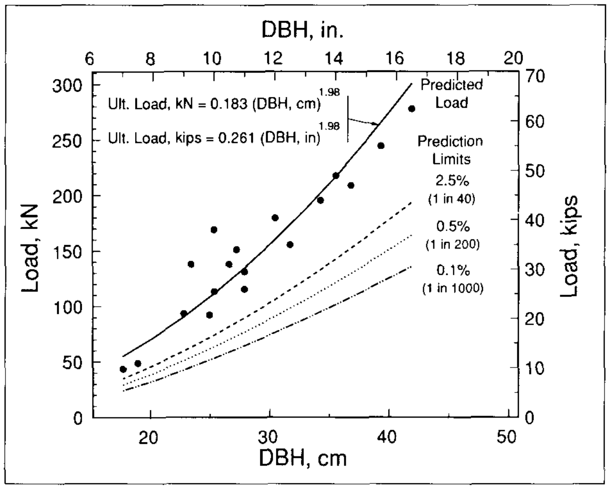

Figure 5. Ultimate load test results for Douglas-fir. Adapted from [4].

Measured Ultimate Load

The ultimate load carried by each Douglas-fir stump is shown in Figure 5. Also shown are a best-fit power function through the data that provides a measure of stump-to-stump difference in load capacity related to DBH, and a family of lower one-tailed prediction limits (2.5%, 0.5%, and 0.1%) for the population represented by the data.

The ultimate load carried by hemlock stumps of each rooting type and at each site is illustrated in Figure 6a. A comparison of regressions for ultimate load as a function of DBH between the two field sites and the stump rooting types did not clearly indicate whether the stump rooting type or the site resulted in a statistically significant difference in ultimate load (Table 2). By visual observation the combined set of stilt rooted stumps appeared to be somewhat weaker than the combined set of normally rooted stumps, but a statistically significant difference was found only for the Forks data.

The picture is further confused by the fact that the largest stump in the data set, a normally rooted one, had an ultimate load well below the pattern of the rest of the stumps, whether normal or stilt-rooted. Careful review of the test data did not indicate any reason to eliminate it from the data set. It is most likely a true reflection of the extreme variability in ultimate load that only showed up on the low side in this data set and would be represented both above and below the average in a larger set. A clearer

Table 2. Summary of Comparisons of stump rooting types and test sites for western hemlock stump anchors.

Data Subset Being Compared	Difference ($\alpha = 0.05$)
Stilted rooted versus regular rooted	
Quinault site	NS[a]
Forks site	S[b]
Both sites combined	NS
Quinault site versus Forks site	
Stilt rooted stumps	NS
Regular rooted stumps	S
Both types combined	NS

[a] Not Significant
[b] Significant

picture of differences or equalities could certainly be obtained from a larger data set.

It is our engineering judgement that until a much larger data set is available, it is best to treat the entire data set as homogeneous (Figure 6b). This will ensure that the strongest, but more importantly the weakest stumps are reflected in the ultimate-load relationship and in the relations between load and movement thereby allowing a set of safe stump-load relationships to be developed. A best-fit power function through the combined data and a family of lower one-tailed prediction limits are also shown in Figure 6b.

Relation Between Load and Movement

The relation between load and movement for a stump anchor was found by Pyles and Stoupa [4] to be very close to a hyperbolic function of the form

$$Load = \frac{1}{\frac{\beta_0}{movement} + \beta_1} \tag{1}$$

The coefficients β_0 and β_1 can be evaluated for any record of load versus movement by linear regression on transformed variables. The R^2 values for equation (1) ranged from 0.986 to 0.998 (all significant at $P < 0.01$) for the Douglas-fir tests [4] and from 0.976 to 0.999 (all significant at $P < 0.01$) for the western hemlock tests. In addition to accurately modeling the relation between measured load and movement, the hyperbolic function has the added advantage that $1/\beta_1$ estimates the ultimate load the stump can carry (Figure 4).

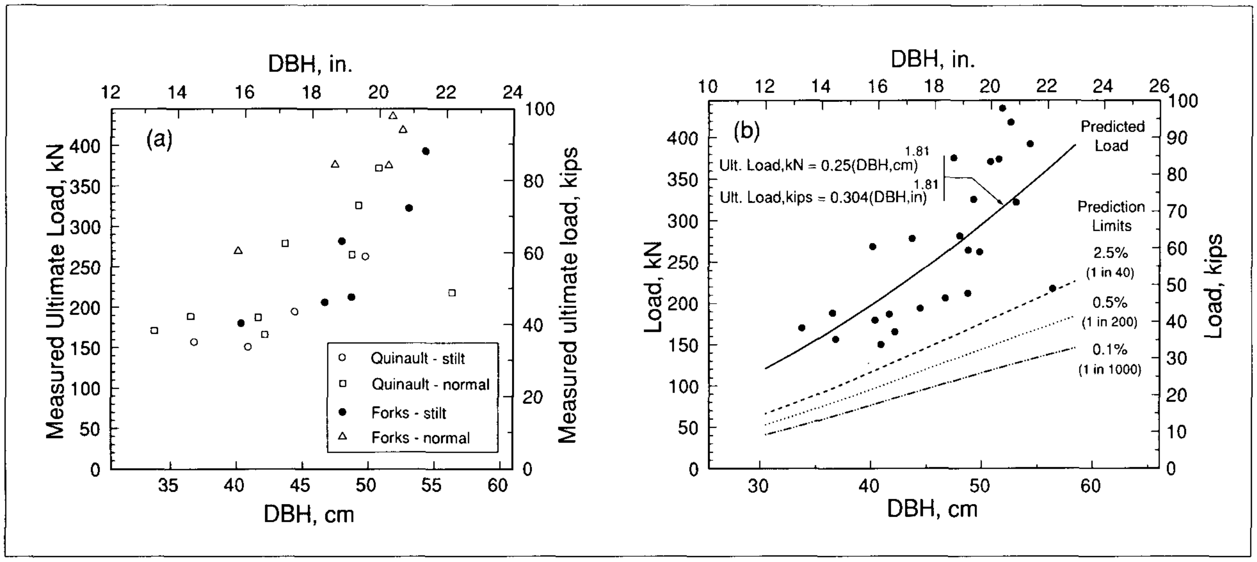

Figure 6. Ultimate load test results for (a) normally rooted and stilt-rooted western hemlock stumps from the two sites and (b) all these stumps combined.

Describing stump behavior with equation (1) allows us the flexibiliby to select the load that correspnds to an appropriate movement as the allowable capacity of a stump. Different rigging configurations and site conditions as well as the experience of the loggers can dictate different allowable movements on a case-by-case basis.

Practical use of a hyperbolic relationship requires that it be generalized to reflect between stump variations in the relation between load and movement. This can be done for variation related to stump diameter if the regression coefficients $\hat{\beta}_0$ and $\hat{\beta}_1$ from the individual stump relationships are treated as variables dependent on DBH in a further regression analysis [4]. Direct multiple linear regression of the hyperbolic form with both movement and stump DBH as independent variables cannot be performed, because the model is intrinsically non-linear. The nearest equation form for which multiple linear regression can be performed on transformed data is

$$Load = \beta_0 \bullet movement^{\beta_1} \bullet DBH^{\beta_2} \quad (2)$$

where the coefficients β_0, β_1, and β_2 are fitted from the data.

Use of equation (2) for a general representation of the load-carrying capacity of stump anchors has two problems. First, the power function form increases continuously with increasing movement, yielding no maximum capacity for a stump anchor. Second, the data from which an equation is developed are serially correlated with respect to movement; that is, the value of load at a given stump movement is related to the load at the previous movement values. The first problem means that the acceptability of the power function form is doubtful. The second problem means that prediction limits for the regression equation will no longer be strictly applicable because the standard deviation of the estimated regression coefficients, as calculated by ordinary least squares regression, may seriously underestimate the true standard deviation [2]. This second problem is critical because an important aspect of predicting an allowable capacity for a stump anchor is knowing the probability that the capacity will be less than the prediction.

The problem with serial correlation — characteristic of numerous types of data — can be eliminated by discrete analysis of the data. The full data set and details of the analysis are presented by Pyles et al. [5]. A brief summary of the steps in the discrete analysis follows:

1. The data from the stump tests are broken into classes on the basis of stump movement, i.e., from each stump test the load that corresponds to 0.635, 1.27, 1.90 cm [0.25, 0.5, 0.75 inches], etc., is selected and grouped with all the other load values for that movement value.

2. Within each stump movement class, regression is used to obtain a relationship between stump diameter (independent variable) and load (dependent variable). Since the best relationship between stump diameter and ultimate load was found to be close to a power function (Figure 5, Figure 6), this relationship within an individual movement class also should be expected to be a power function.

3. Prediction limits from these regressions will allow us to estimate, for a particular size of stump, the load that corresponds to a givenprobability of being exceeded, or conversely, a given probability of not being reached. These prediction limits are statistically rigorous and can be used directly to obtain discrete loads for a particular size of stump at each of the stump movements considered.

Further practical benefit can be gained by modeling the relationships among stump diameter, movement, and load that are implied in the results of the regression analysis. This can be done by developing a synthetic data set made up of load estimates at a range of stump movements for a range of stump diameters, modeling that synthetic data set with equation (1), and then treating the coefficients further as dependant on DBH just as reported for the raw data by Pyles and Stoupa [4], and Pyles et al. [5]. The net result is a set of equations for selected prediction limits that gives stump load as a function of stump size and movement under that load (Table 3). On the average, the equations accurately describe the mean load values and prediction limits, because the hyperbolic equation is an exceptionally good fit to the actual stump test data. Locally, differences between the equation and the true prediction limits amount to as much as 7% in load (Figure 7).

These errors can be viewed in two ways: first, as a simple error in the load that corresponds to a given prediction limit, or second, as an error in the actual prediction limit. For example, if the true 0.05% prediction limit (1 in 200) for 45.7 cm diameter [18 inch] hemlock stump anchor at 2.54 cm [1 inch] of movement is 116.9 kN [26.3 kips], while the equation from Table 3 gives a value of 111.6 kN [25.1 kips], then an error of 4.6% in load exists. Viewed as an error in prediction limit, a load of 111.6 kN [25.1 kips] by interpolation corresponds to a .25% prediction limit (1 in 400). Errors of these magnitudes between the equations and the true values, either in terms of load or prediction limit, can be easily accommodated in the selection of stump anchors.

RECOMMENDED METHOD FOR DETERMINING STUMP ANCHOR CAPACITY

We suggest that there should be two criteria for selecting stump anchors for a cable-logging operation: (1) The anchors should be of sufficient size so that an acceptably small number of them will deform more than the allowable amount, requiring either a tie-back or re-rigging to a different stump, and (2) the anchors should be of sufficient size so that

Table 3. Coefficients for the hyperbolic stump capacity function:

$$Load, kN = \frac{1}{\frac{f_1(DBH, cm)}{movement, cm} + f_2(DBH, cm)}$$

Species	One-tailed prediction limit[a]	$f_1(DBH, cm)$	$f_2(DBH, cm)$
Douglas-fir	50% (1 in 2)[b]	42.498 DBH $^{-2.5466}$	3.8824 DBH $^{-1.8666}$
	2.5% (1 in 40)	35.204 DBH $^{-2.2446}$	3.4390 DBH $^{-1.7212}$
	0.5% (1 in 200)	34.591 DBH $^{-2.1504}$	3.2266 DBH $^{-1.6647}$
	0.1% (1 in 1000)	34.555 DBH $^{-2.0666}$	2.9989 DBH $^{-1.6097}$
Western hemlock	50% (1 in 2)[b]	2.6951 DBH $^{-1.7831}$	2.8481 DBH $^{-1.7381}$
	2.5% (1 in 40)	11.154 DBH $^{-1.9858}$	6.4335 DBH $^{-1.8531}$
	0.5% (1 in 200)	18.322 DBH $^{-2.0561}$	8.4755 DBH $^{-1.8909}$
	0.1% (1 in 1000)	28.787 DBH $^{-2.1199}$	10.814 DBH $^{-1.9236}$

aThe percent (or ratio) by which stump anchors will have a lower capacity than the hyperbolic equation predicts.
[b]Mean or average load-movement value.

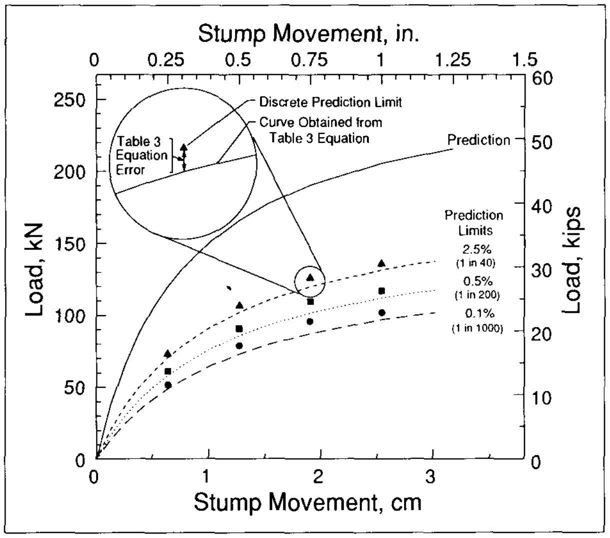

Figure 7. Discrete one-tailed prediction limits to load test data and equation estimates of the relation between load and movement for a 45.7 cm [18-in.] western hemlock stump anchor.

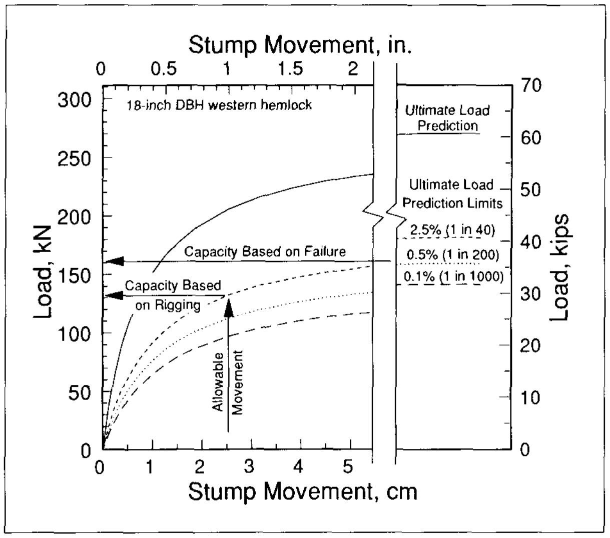

Figure 8. Use of the relationships between stump-load and movement in estimating stump anchor capacity.

there is an acceptable incidence of total failure with the stump pulling out of the ground. The first criterion is an operational one consistent with the standard practice of periodically monitoring guyline and tailhold stumps during the logging operation. The second criterion is based on the premise that injury-causing accidents will occur but that we should work to limit them. Depending on the species, site, logging system, and the timber being logged, one of the two criteria will control stump anchor selection.

Selecting the allowable capacity of a stump anchor on the basis of the two criteria mentioned above requires an estimate of the probability of needing to re-rig a particular size stump anchor, and the probability that a complete pull-out failure will occur at the applied load. The equations in Table 3 provide estimates of both probabilities for a given stump size and allowable movement. The use of the equations can be detailed in a series of steps (illustrated graphically in Figure 8):

1. Select the *allowable stump anchor movement* that will be used to judge when re-rigging is required during the logging operation (Figure 8; e.g., 2.54 cm [1 inch]). This should be a movement normally considered as a sign of impending failure of an anchor. It should also be a value observable either by eye or by a simple measurement.
2. Select the frequency with which you are willing to have to re-rig anchors (Figure 8; e.g., 1 in 40). This value should be selected to balance the amount of re-rigging with initial multi-stump rigging. If a very low frequency of re-rigging is selected, then the allowable capacity of the stumps will be very low, requiring costly initial rigging of multi-stump anchors. If a high frequency is selected, the delay in operations required to re-rig anchors may exceed the cost of initially rigging multi-stump anchors.
3. Using the appropriate load-movement equation (Table 3), solve for the load at the allowable movement from step 1 (Figure 8; e.g., capacity based on rigging = 131.2 kN [29.5 kips]). This will be called the re-rigging load because it represents a load selected using the re-rigging criteria.
4. Select the frequency of pull-out failure that you are willing to accept, and compare the load from step 3 with the ultimate load for the frequency of failure (Figure 8; e.g., capacity based on failure = 160.1 kN [36 kips]. Selection of this value can be based on current failure rates and accident rates. If current failure rates are judged to be unacceptable, a lower frequency can be selected.

5. If the failure load is greater than the re-rig load, the re-rig load controls the allowable capacity; if the failure load is less than the re-rig load, then the failure load controls the allowable capacity (Figure 8).

6. Continually re-evaluate the selected re-rigging frequency (Step 2) and the pull-out failure frequency on the basis of actual field performance.

SUMMARY

The data presented on stump anchor tests are a first step in developing the broader data set that will be required to estimate stump-anchor capacity under a wide range of field conditions. Caution should be used in applying the capacity equations presented to sites other than where the testing was done. Site and stand differences could yield significant differences in stump anchor capacity. The load direction implicit in the capacity equations is parallel to ground. The literature indicates that the capacity of stump anchors with a large normal to hillslope component load component is less than the parallel-load capacity [3], but field data is not exhaustive enough for a load angle adjustment coefficient to be obtained.

Despite these restrictions, the analysis provides a rational interpretation of stump anchor capacity that can easily be incorporated into cable-logging practice, and it should be applicable to future data sets. Even with a larger, more broadly applicable data base however, the use of failure statistics and the concept of probability of failure will have to be accepted in cable logging for effective use of the method presented.

LITERATURE CITED

[1] Gere, James M. and Stephen P. Timoshenko. 1984. Mechanics of Materials. Second Edition, PWS Publishers, Boston, Mass. 762 p.

[2] Neter, J., W. Wassermann, and M. Kutne. 1983. Applied Linear Regression Models. Richard D. Irwin, Inc., Homewood, Ill. 547 p.

[3] Peters, Penn A. and Cleveland J. Biller. 1985. Preliminary evaluation of the effect of vertical angle of pull on stump uprooting failure. Proc. 9th Annual Council on Forest Engineering Meeting. Mobile, AL. Sept. 20-Oct. 2. pp. 90-93.

[4] Pyles, Marvin R. and Joan Stoupa. 1987. Load-Carrying Capacity of Second-Growth Douglas-Fir Stump Anchors. Western Journal of Applied Forestry 2(3):77-80.

[5] Pyles, Marvin R., W.L. Schroeder, Joan Stoupa, Richard Toupin, and Jerry W. Anderson. 1987. Stump-Anchor Testing. Final report to the Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. Research Agreement Supplements No. PNW-82-332 and PNW-85-379.