What if Trees Had Ratings in kN? Tree Anchor "Ratings" Based on Wind Loading
John Morton, Snohomish County SAR / Everett Mountain Rescue

When technical rescuers arrive at a scene that may involve rope access, among the first things we do is evaluate potential anchors for useful location and adequate strength. Most us have been taught (and then perhaps repeated as instructors) that adequate anchors are foundational to a safe and effective rope rescue system. Most of us have been taught (and then perhaps repeated as instructors) that a living, well-rooted tree is an adequate rescue anchor, provided the trunk is helmet-sized or larger. Specifically, a helmet-sized tree has sufficient strength to withstand forces we might apply via our rope system.

Ideally, it would be convenient if each tree had a carabiner-like "strength rating" placard clearly indicating how much anchor loading that tree is known to withstand. While we are dreaming, it would be even better if that tree's load capability were demonstrated by testing, since trees do not have tight manufacturing controls. Rather than a test-based strength rating, trees just have this often-repeated "rule" that helmet-sized is strong enough. But is that really all we have to judge tree strength?

People who spend time outdoors will sooner or later witness a group of trees bearing the onslaught of a powerful windstorm. When we watch our wooden giants getting rocked by the wind gods, it is a compelling and humbling reminder of the small scale we humans typically experience. A technical rescuer might watch such a windstorm and think something like, "Wow, those trees are handling forces far, far beyond anything we can bring to bear using our puny little rope systems." Hmmmmm…

How much wind would a tree need to withstand to show itself adequate to carry equivalent loading that might be applied through a rescue anchor? That probably depends on the type of tree. And how tall is the tree. And what nearby trees deflect some of the wind. And soil conditions. And terrain. And root structure. And perhaps other things that might be difficult to nail down.

When technical rescuers arrive on scene, we can be confident of two things about a living, standing tree: 1) the tree has been exposed to some amount of wind, and 2) the tree has been able to withstand the forces resulting from that wind. If our rescue teams had some method to translate a tree's strength that has already been proven by wind into equivalent anchor strength (a "wind rating"), then we could make a reasoned decision about using or not using a candidate anchor in our rope system. More anchor choices. Favorable placement for rope alignment. Less rope stretch using anchors closer to the edge. Faster setup. These and other reasons motivate us to consider the widest array of credible rescue anchors.

But to be practical, a method to determine "wind rating" would need to be appropriate for field use. It would need to work with a range of rescuer fluency, and when applied under the time pressure, weather, fatigue, and life safety conditions that define our missions. Anchor selection during a rescue cannot deteriorate into scientific research on scene. No committees. No magic. Plenty of margin.

Certainly this method includes some complexity: mechanical engineering, and numerical modeling, and meteorology (weather), and dendrology (trees), and perhaps some testing (measure and break things). However, the objective of this project is simple: develop a mission-appropriate method that gives go/no-go adequacy of "smaller" trees for use as rescue anchors.

Understanding how a tree tells us what anchor strength it has

Long before our rescue teams arrive to consider a tree as a potential rescue anchor, that tree has been exposed to a variety of natural forces. Depending on climate, a surviving healthy tree will have tolerated effects of wind, precipitation, snow loading, impact from tree or rock fall, etc. As a surrogate for forces applied by a rescue anchor, wind force has the advantage of imparting substantial bending/shear load, much like a rescue anchor would apply. Also, characterizing wind loading on trees can draw on techniques related to predicting wind effects on man-made structures, such as skyscrapers or antennae.

The heart of this project is a force model that has three key elements:
- Determine how much wind reaches a particular sized "smaller" tree
- Determine the force applied to a tree by the wind that reaches it
- Translate force from wind into equivalent force applied by a tensioned rescue anchor.

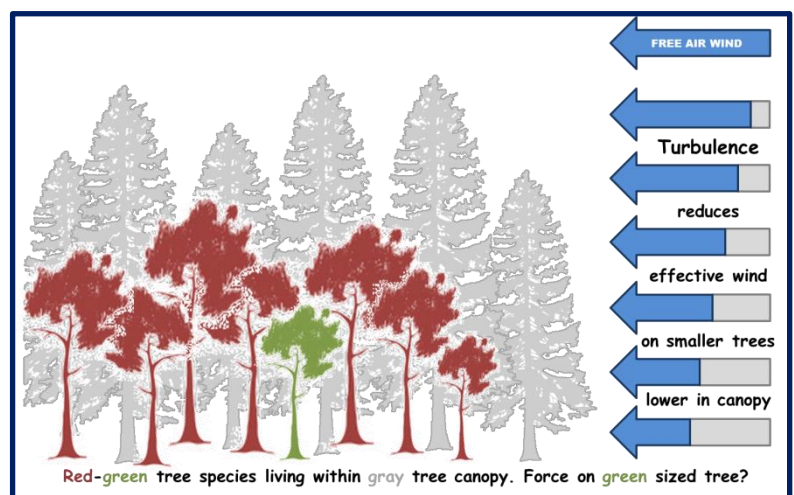Three additional elements enable the force model and compile useful results:
- Establish an aerodynamic profile for trees that are anchor candidates
- Calculation tool to examine a range of tree size, over a range of wind speed, for many tree species
- Produce results that can be consumed by rescue teams, including during an active mission.

Previous work has established that detrimental effects on trees used as rescue anchors are primarily related to bending and shear load that compromise the base and root system. Other theoretical failure mechanisms, destruction of the wood itself for example, are not what limits our ability to use a particular tree in a rescue system. *Rick Weber, "How to Determine Tree Strength", ITRS 2010*

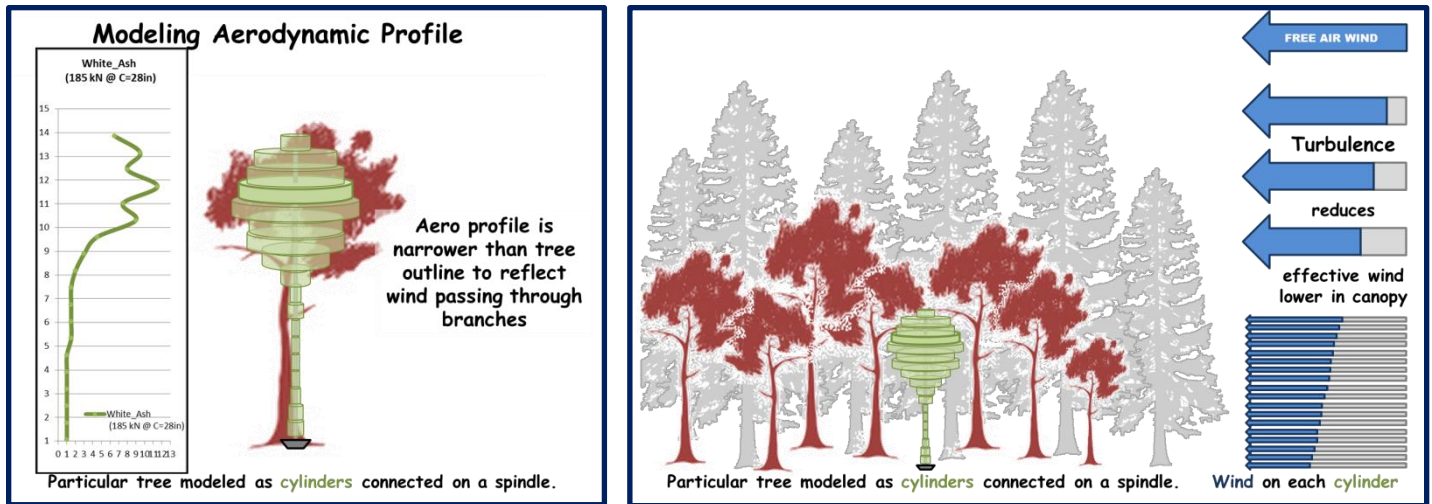## Turbulence model: how much wind reaches a smaller tree?

Modern weather-related data gives fairly thorough indication of wind throughout a region. Example access points might include National Weather Service websites, Weather Underground, and various aviation weather resources. During seasonal high wind events, the upper end of sustained wind speed is shown here as "free air wind" speed. Wind speed in free air is related to, but not the same as the wind that impacts smaller trees within a canopy. Lower in the canopy, wind speed and the resulting forces are reduced as the moving air becomes turbulent.

In addition, the speed of turbulent air varies within the canopy, such that the wind speed toward the top of a mid-sized tree is not the same as further down that same tree. Finally, a tree species may be intermixed with other taller species, so that the canopy is determined by trees taller than a full-sized example of the species under consideration. For purposes of force calculations in this model, turbulent wind below the canopy is "sliced" into decreasing wind speeds moving lower in the canopy.

Red-green tree species living within gray tree canopy. Force on green sized tree?

FREE AIR WIND
Turbulence
reduces
effective wind
on smaller trees
lower in canopy

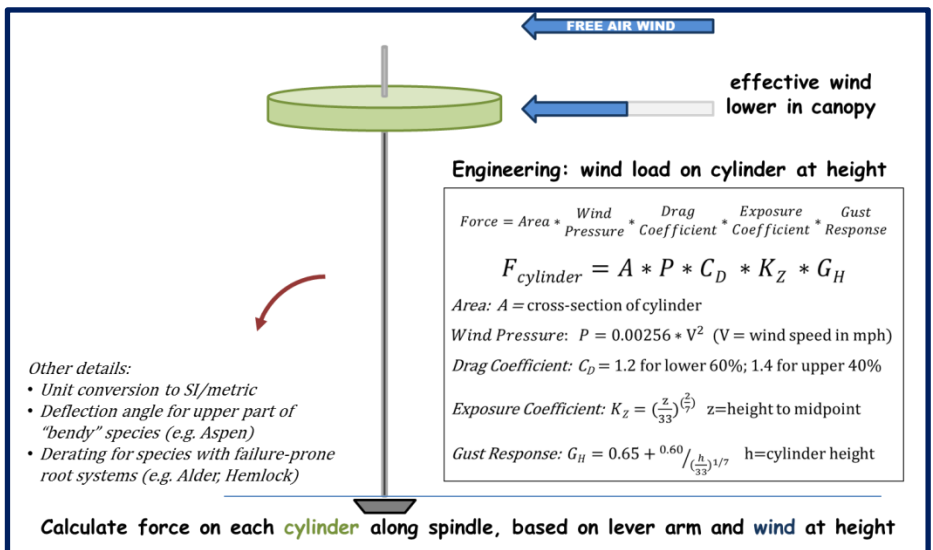# Aerodynamic profile: representing a tree as a stack of spindled cylinders

There is considerable variation among individual real-world trees -- even of trees of a single species. For this wind force model, a species tree is simplified as a representative stack of 20 cylinders on a spindle anchored at its base. Each cylinder represents 5% of the tree height, but is narrower than the tree outline in order to conservatively address variation among individual trees. In the crown portion of the tree, the diameter of the cylinders are well within the tree outline to represent wind passing through branches with comparatively less force on the base.

Modeling Aerodynamic Profile. White_Ash (185 kN @ C=28in). Aero profile is narrower than tree outline to reflect wind passing through branches. Particular tree modeled as cylinders connected on a spindle.

FREE AIR WIND. Turbulence reduces effective wind lower in canopy. Particular tree modeled as cylinders connected on a spindle. Wind on each cylinder.

Tree species data in the model also include a relationship between base circumference and tree height, as well as canopy height of neighboring species. Where there is variability, such as canopy height of neighboring species, profile data are chosen conservatively. Tree shape parameters and information about neighboring species (canopy) are drawn from references such as United States Forest Service Silvics Manual, and the Audubon Society Field Guide to TREES.

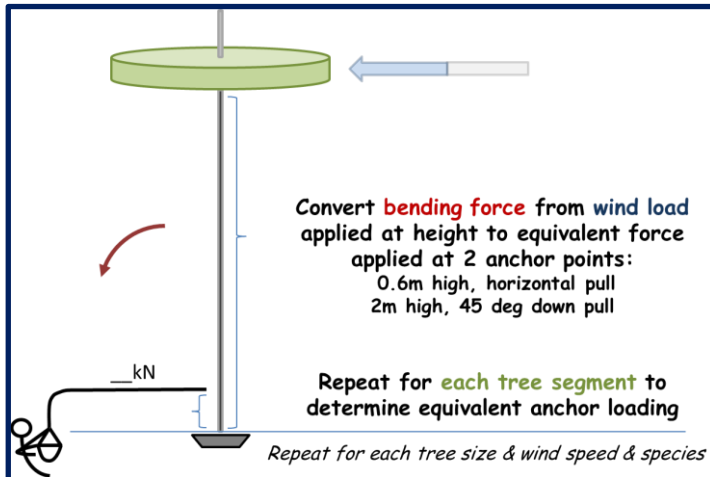# Engineering magic: Calculating wind force on cylindrical structure

Once a turbulent wind profile and aerodynamic tree shape are established, they are aligned at ground level. Then force is calculated for one cylindrical segment at a time. Wind loading on a cylindrical body at height (reacted at its base) is well understood from design of skyscrapers and antennae. While the calculations have somewhat complex exponential terms, the relevant formulae are readily available, even just a Google search away. (One example among many: www.wikihow.com/Calculate-Wind-Load)

FREE AIR WIND. effective wind lower in canopy.

Other details:
- Unit conversion to SI/metric
- Deflection angle for upper part of "bendy" species (e.g. Aspen)
- Derating for species with failure-prone root systems (e.g. Alder, Hemlock)

Engineering: wind load on cylinder at height

$$Force = Area * \frac{Wind}{Pressure} * \frac{Drag}{Coefficient} * \frac{Exposure}{Coefficient} * \frac{Gust}{Response}$$

$$F_{cylinder} = A * P * C_D * K_Z * G_H$$

Area: A = cross-section of cylinder

Wind Pressure: $P = 0.00256 * V^2$ (V = wind speed in mph)

Drag Coefficient: $C_D = 1.2$ for lower 60%; 1.4 for upper 40%

Exposure Coefficient: $K_Z = \left(\frac{z}{33}\right)^{\left(\frac{2}{7}\right)}$ z=height to midpoint

Gust Response: $G_H = 0.65 + 0.60/\left(\frac{h}{33}\right)^{1/7}$ h=cylinder height

Calculate force on each cylinder along spindle, based on lever arm and wind at height

The base of the tree carries wind load accumulated over the entire tree length, demonstrating the tree's ability to carry bending and shear force. This is the same load carrying capability we rely upon for a rescue anchor.

Mechanics: translate wind force into equivalent anchor

Perhaps the most straightforward part of this project is translating force applied to a tree at height to an equivalent force applied at the location of a rescue anchor. This translation is calculated segment by segment, using techniques that would be familiar to a mechanical engineering student.

Convert **bending force** from **wind load** applied at height to equivalent force applied at 2 anchor points:
0.6m high, horizontal pull
2m high, 45 deg down pull

Repeat for *each tree segment* to determine equivalent anchor loading

Repeat for each tree size & wind speed & species

It is worth noting that these calculations correlate wind force over the entire tree length to an equivalent anchor force applied horizontally at a height of 0.6 meter (2 feet). This is deliberately not as low as a rescue anchor could be placed on a real-world tree. Moving an anchor lower on a tree provides on-scene rescuers an option that adds margin beyond these results. Depending on risk factors, placing an anchor very low on a tree may allow responsible use of an anchor that calculates as "marginal" at 0.6 meter anchor height.

A similar set of results is compiled that correlates wind force over the entire tree length to an equivalent high-directional anchor force applied 45 degrees below horizontal at a height of 2 meters. Once again, this is conservative as a typical high directional pulls more vertically than 45 degrees. Here also, on-scene rescuers have the option of placing high directional anchors lower than 2 meters if that helps a marginal strength tree.
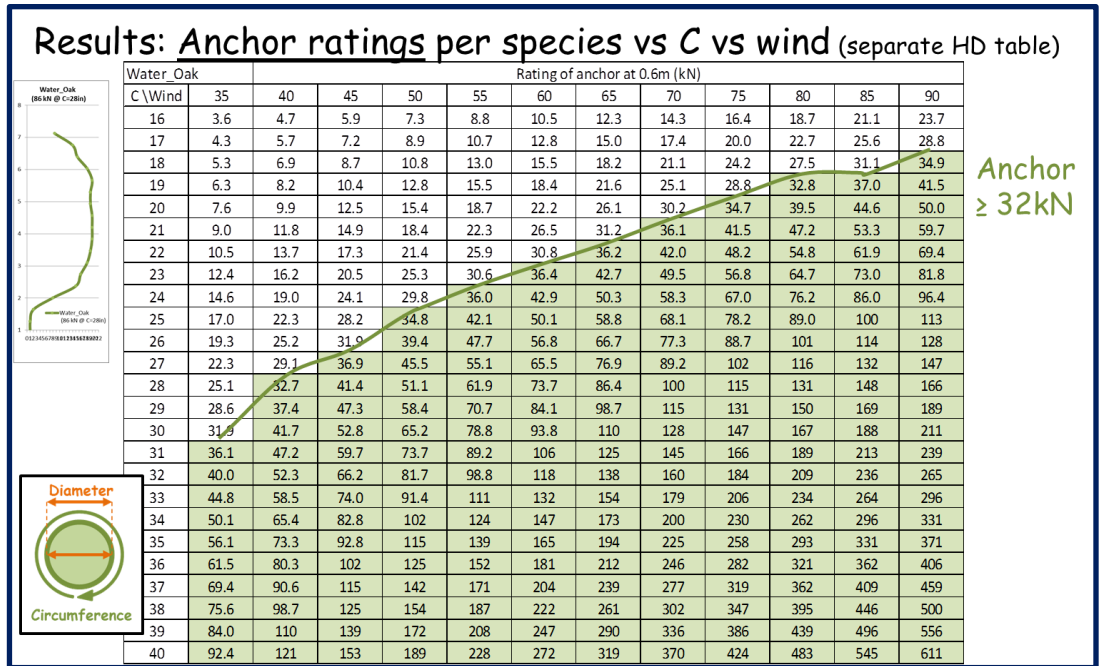
Number crunching: repeat for each tree segment, tree size, wind speed, species

It would be possible to hand-calculate the turbulent wind profile under a species canopy, then identify the resulting wind impacting a "modeled tree" cylindrical segment of particular height and diameter. Then one could calculate the wind forces applied at the lever arm that is the height of the cylinder above the ground. Possible, but tedious to hand calculate. So, we will leave that to the computer.

This project includes a rudimentary computer program to repeat the wind loading calculations for 20 segments per tree. Then the cycle is repeated for each increment in tree circumference for that species. Then that entire calculation for various tree sizes is repeated over a range of free air wind speed. Then the size/wind speed cycle is repeated for each tree species of interest.

As the calculations repeat for increasing tree circumference, the 20-segment aerodynamic tree model is scaled accordingly. This extends the slightly taller tree model higher into turbulent wind, as well as exposing slightly wider cylinders to that wind. Both factors tend to drive increased wind force, though the relationship is not linear – for example, a 2% increase in tree size results in more than a 2% increase in force applied to the tree. Likewise, a 5% increase in wind speed results in more than a 5% increase in force applied to the tree. The details are complicated, but manageable in small steps.

As the calculations repeat for each wind speed, the turbulence model is adjusted and calculations repeated over the range of tree sizes (circumference in inches). As the calculations repeat for each tree species, the associated canopy determines the turbulence profile that applies.

Results: Anchor ratings per species vs C vs wind (separate HD table)

| Water_Oak						Rating of anchor at 0.6m (kN)						
C\Wind	35	40	45	50	55	60	65	70	75	80	85	90
16	3.6	4.7	5.9	7.3	8.8	10.5	12.3	14.3	16.4	18.7	21.1	23.7
17	4.3	5.7	7.2	8.9	10.7	12.8	15.0	17.4	20.0	22.7	25.6	28.8
18	5.3	6.9	8.7	10.8	13.0	15.5	18.2	21.1	24.2	27.5	31.1	34.9
19	6.3	8.2	10.4	12.8	15.5	18.4	21.6	25.1	28.8	32.8	37.0	41.5
20	7.6	9.9	12.5	15.4	18.7	22.2	26.1	30.2	34.7	39.5	44.6	50.0
21	9.0	11.8	14.9	18.4	22.3	26.5	31.2	36.1	41.5	47.2	53.3	59.7
22	10.5	13.7	17.3	21.4	25.9	30.8	36.2	42.0	48.2	54.8	61.9	69.4
23	12.4	16.2	20.5	25.3	30.6	36.4	42.7	49.5	56.8	64.7	73.0	81.8
24	14.6	19.0	24.1	29.8	36.0	42.9	50.3	58.3	67.0	76.2	86.0	96.4
25	17.0	22.3	28.2	34.8	42.1	50.1	58.8	68.1	78.2	89.0	100	113
26	19.3	25.2	31.9	39.4	47.7	56.8	66.7	77.3	88.7	101	114	128
27	22.3	29.1	36.9	45.5	55.1	65.5	76.9	89.2	102	116	132	147
28	25.1	32.7	41.4	51.1	61.9	73.7	86.4	100	115	131	148	166
29	28.6	37.4	47.3	58.4	70.7	84.1	98.7	115	131	150	169	189
30	31.9	41.7	52.8	65.2	78.8	93.8	110	128	147	167	188	211
31	36.1	47.2	59.7	73.7	89.2	106	125	145	166	189	213	239
32	40.0	52.3	66.2	81.7	98.8	118	138	160	184	209	236	265
33	44.8	58.5	74.0	91.4	111	132	154	179	206	234	264	296
34	50.1	65.4	82.8	102	124	147	173	200	230	262	296	331
35	56.1	73.3	92.8	115	139	165	194	225	258	293	331	371
36	61.5	80.3	102	125	152	181	212	246	282	321	362	406
37	69.4	90.6	115	142	171	204	239	277	319	362	409	459
38	75.6	98.7	125	154	187	222	261	302	347	395	446	500
39	84.0	110	139	172	208	247	290	336	386	439	496	556
40	92.4	121	153	189	228	272	319	370	424	483	545	611

Anchor ≥ 32kN

For each tree species, the calculations result in two tables listing anchor strength values for a range of tree size and wind speed. One table is for a horizontal rescue anchor set at 0.6 meters, and another table for high directional set at 2 meters and pulled 45 degrees below horizontal. From these force data, a variety of tables and charts are built to be applied by rescue teams.

Results: collect the data in various formats, including field-deployable guides

The model output collects results for up to 12 tree species per designated region. Results include material that enables "sanity checks" -- data not intended to be field deployable. One example shows full-strength anchor size vs wind speed for 12 tree species (shown on left).
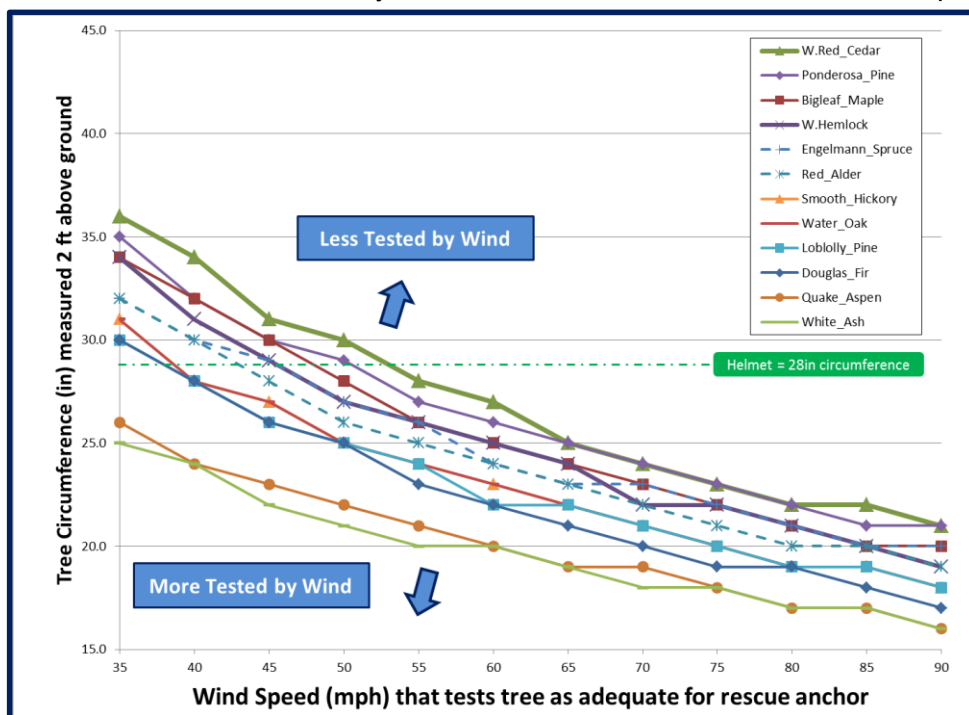
But the most valuable results are pages that can be included with field gear that enable rescue teams to make go/no-go anchor decisions on scene (next page).

The inputs required to produce region-applicable "field guides" include free air wind speed (typically upper end of sustained wind during storms) and also the threshold of choice for rating of a "full strength" rescue anchor.

Trees smaller than helmet-sized (28 in circumference) may be used as rescue anchors by following these criteria. If in doubt about anchor integrity, use other material or back up anchors as appropriate.		
☑ Tree is living & structurally sound		
☑ Tree has vertical trunk, including base		
☑ Rooted in normal soil (not sand or gravel), without voids		
☑ Tree has symmetrical base at ground level		
Measure circumference around tree @ 2 ft above ground (incl for Ratings based on ANCHOR @ 2 ft and HIGH-D @ 7 ft		
Wind rating data applies *[location description defining region familiar to rescue team]*. Applies from Mmm-20xx through Mmm-20xx		
Identify tree species, or use largest Circumference	Minimum Circumference for ANCHOR	Minimum Circumference for HIGH-D
W.Red_Cedar or UNKNOWN species	>24in	>32in
Ponderosa_Pine	>24in	>30in
Bigleaf_Maple	>23in	>30in
W.Hemlock	>23in	>29in
Engelmann_Spruce	>22in	>28in
Red_Alder	>22in	>28in
Smooth_Hickory	>21in	>27in
Water_Oak	>21in	>26in
Loblolly_Pine	>21in	>26in
Douglas_Fir	>20in	>26in
Quake_Aspen	>18in	>22in
White_Ash	>18in	>22in

Field Guide – front side

For the purposes of illustration, these results show a fictitious "ITRS2015 region", which includes a sampling of trees from across North America. To create sample field guide pages, these results were run with a "rating" of 65 mph as free air wind speed, and 32 kN as threshold for a full-strength anchor. Note that these inputs do not affect the tree or wind models, nor on the force calculations for various sized trees. Rather, these fully-adjustable inputs only determine which results are collected into field guide pages.

There must be some time element to these results. Wind that a tree was exposed to 10 years ago is not a compelling indicator of that tree's strength today. In the Pacific Northwest, our seasonal wind events are typically in December through March. Our SAR team expects to update these field guide pages each spring, based on winds during the preceding months. Then the results are considered valid for about 1.5 years (through two summer rescue seasons).

It is important to note that wind rating values do not indicate true breaking strength of a tree. Rather, they show an anchor force the tree can withstand based on wind forces the tree has already withstood. A tree may be considerably stronger than these values suggest. This is particularly true for triangular-profile trees, such as Western Red Cedar. These have a

fairly thick trunk for their height, and most of their sail area is low to the ground. For example, in the same wind storm, wind force on a 20-inch circumference Red Cedar would be less than a 20-inch White Ash. Yet the Red Cedar may in fact be stronger than the same sized White Ash – just not as thoroughly tested by wind forces. While the additional strength beyond the wind rating is difficult to quantify, the margin is in the direction of safety.

Region: ITRS --- seasonal wind = 65 mph

Circumf (inches) wind tested at 65mph	Douglas_Fir	Engelmann_Spruce	Loblolly_Pine	Ponderosa_Pine	Water_Oak	W.Hemlock	W.Red_Cedar (?)	Bigleaf_Maple	Quake_Aspen	Red_Alder	Smooth_Hickory	White_Ash
16	13.9	9.1	12.1	7.7	12.3	9.4	7.1	9.2	17.0	9.8	11.3	18.1
17	17.1	11.2	14.8	9.3	15.0	11.7	8.9	11.4	21.9	12.3	14.1	22.8
18	20.7	13.5	18.1	11.4	18.2	14.0	10.7	13.7	27.4	15.2	17.3	29.2
19	24.6	16.3	21.9	13.5	21.6	17.0	13.0	16.5	34.1	18.6	21.2	36.8
20	29.1	19.8	26.4	15.9	26.1	20.1	15.3	19.5	42.3	22.0	25.5	45.6
21	34.0	23.5	31.7	18.9	31.2	23.8	18.2	23.0	51.1	26.4	30.6	56.7
22	39.5	27.3	37.7	22.4	36.2	27.7	21.1	26.7	61.7	31.5	35.5	68.8
23	45.7	32.4	43.4	26.4	42.7	31.9	24.8	31.1	74.6	36.3	41.7	83.6
24	52.4	37.6	51.1	30.2	50.3	37.1	28.4	35.6	87.7	42.5	47.8	97.8
25	59.7	44.4	58.2	35.2	58.8	42.3	33.0	40.9	103	49.4	55.7	116
26	67.8	50.3	67.6	40.9	66.7	47.9	37.4	46.4	122	56.0	64.2	135
27	77.7	58.2	76.3	46.2	76.9	54.1	42.2	52.3	139	64.4	73.8	156
28	89.7	66.4	87.3	53.0	86.4	61.8	47.5	58.8	163	73.4	84.7	185
29	100	76.4	97.8	59.3	98.7	70.0	54.0	66.1	182	84.2	98.1	207
30	116	86.4	112	67.6	110	78.0	60.2	73.8	214	97.5	109	239

Field Guide – reverse side

To be useful, this method to determine "wind rating" needs to be appropriate for field use during a rescue mission. It needs to work with a range of rescuer fluency, and when applied under the time pressure, weather, fatigue, and life safety conditions that define our missions. It has to be repeatable by different team members and on different days. It has to fit into normal team training.

Printed on two sides and laminated, this field guide has a simpler side, and an almost-as-simple reverse side. Using the super simple front side, a rescuer armed with the laminated page and 3-foot tape measure can consistently determine go/no-go for a prospective anchor tree. The ability to distinguish species improves tree options, but is not critical to consistent go/no-go decision.

Using the reverse side, and armed with the tape measure, a sharpie, and some pink and green flagging, a team could send NewGuy ahead to measure and label candidate anchor trees in the operational area. Flagging would indicate go (green) vs no-go (pink), as well as strength ratings in kN. This would literally result in anchor trees having the physical equivalent of a rating stamp like a carabiner or pulley. More practical for a real rescue mission, an individual tree's "wind rating" could be looked up, so that anchor decisions can be made in seconds (use it, back-tie, multi-point, don't use it).

Critical Thinking: Do the model results seem reasonable?

Based on extensive pressure testing, this wind force model yields consistent and sensible data. The results compare well to analytical and test data, make sense when comparing one species to another, and also fit anecdotal experience using smaller trees as rope system anchors. As I have previewed the model results with experienced technical rescuers, several questions are frequently asked.

Q: Why 20 tree segments, rather than more or fewer?
A: I tried as few as 12 segments for trees, with marginal results as tree shape nuance had noticeable effect on results for a given wind speed. I also tried more detailed profiles such as 30 or 40 segments. These aero profiles are more difficult to create, yet had little effect on results, compared to 20 segments.

Q: How do model results compare to testing?
A: Rick Weber's work presented at ITRS-2010 is an example of past study and testing showing tree anchors into the 15kN range. This is excellent data, and responsibly tops out when real-world forces begin to pose problems during testing. Once calibrated for anchor height, these test data line up very nicely with model results described here. Such alignment is not conclusive, but it is compelling.

Q: Does this mean rescuers need to learn tree species identification to do their job?
A: If rescuers cannot identify the species of a candidate anchor tree (limited by time or expertise), simply use the species marked to represent "UNKNOWN" (Western Red Cedar in the example set). Identifying tree species allows the rescuer to take full advantage of the tree under consideration, rather than simply using the species with the lowest strength rating on the list (safe but conservative).

Q: What areas of the model are still uncertain, yet have significant effect on the results?
A: Model results depend significantly on the turbulence profile. The current turbulence model shows wind speed decreasing below canopy more than is probably real, which is conservative. I have both model improvements and testing in mind that might allow peeling back some conservatism, which would "turn green" slightly smaller trees as credible rescue anchors. But the differences are small – perhaps an inch or two at most in circumference. A bit of conservatism is not so bad in this technical rescue business.

Conclusion: a healthy tree tells us about the anchor force it can withstand

For regions with only light seasonal wind, limiting anchor selection to helmet-sized or larger trees is reasonable, but conservative. Using 28-inch circumference as a go/no-go criteria means that fully adequate trees would not be used. The overall rescue system may then be less effective, and less safe, for having bypassed potentially better-placed anchor trees. In areas with higher seasonal wind (wind storms greater than 45 mph), even smaller trees can be credible rescue anchors, based on having survived wind loading.

This model offers results that protect system integrity, while being practically deployable in the field. These results are consistent with test data. Testing to failure is quite reasonably limited to modest forces for reasons of safety and practicality. This method extends results from field tests on small trees up to somewhat larger trees.

As always, decisions during rescue operations must align with training and field-appropriate tactics. NO SCIENCE PROJECTS DURING RESCUE MISSIONS! If teams intend to use smaller trees as rescue anchors, then practice how to do that responsibly.

The usual ITRS caveats apply here:
- More testing and research is good
- Carefully consider new data, and apply it prudently
- Do the right thing for your team and your mission.

If my compatriots in the technical rescue community have questions, suggestions, criticisms, or want data for particular tree species, feel free to contact me.

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Authors note: The tree anchor strength model described here first began as a joint project between myself and Mark Miller, of Ouray Mountain Rescue and Rigging for Rescue. Mark is well known in the community of climbers, guides, and technical rescuers, including among those who frequent ITRS events. Ironically, I was working on the presentation of this material for ITRS-2015, when I received the tragic news that Mark had been killed in a fall while ice climbing. So, while Mark was part of the early work portrayed here, he was not able to review the material presented at ITRS. This is the very least among many impacts from losing our brother Mark. –JM