Understanding size-related principles of tree growth for better tree-risk evaluation

Frank Rinn

Abstract: The ratio of tree height over diameter at breast height (H/D) has been used to characterize different aspects of both forest and urban tree growth, for example biomass and stability. Research found a constant H/D-ratio in many forest stand trees after having survived the juvenile growth phase. This is extremely important information for tree-risk assessors because it confirms that H/D is a valid measure for breaking safety. When trees stop growing in height, radial growth, however, continues. This serves to increase the diameter of the trunk cross-section. Consequently, breaking safety continues to increase because load-carrying capacity of a cross section strongly depends on its diameter.

Keywords: height-over-diameter-ratio, wind load, tree breaking safety, tree-risk.

Introduction

The ratio of tree height over breast height diameter (H/D) has been extensively studied in forestry and used, for example, as a parameter characterizing biomass (Picard et.al. 2012) and tree stability (van Gelder et.al. 2006). For conifer forest trees, a nearly constant H/D-value was found over a long period of time (Kahle et.al. 2008): while H/D drops down from values over 100 in the juvenile growth phase, H/D then remains nearly constant for several decades before the trees reach maximum height. For the ratio of tree-height over breast-height diameter to remain constant over such a long period of time, there must be a reason and an internal self-regulating process within trees to do so.

The fact that mechanical stresses influence the growth rate of cambium cells was already reported by Telewski and Jaffe (1986). However, a mathematical description and explanation of the self-regulating process within the tree leading to a constant H/D-ratio was still absent, as well as its implication for tree-risk assessment in arboriculture.

Load and capacity relations

The wind load arriving at the stem base is proportional to tree-height (**Fig. 1**) to the power of approximately three (Rinn 2014):

$M \sim H^{-3}$

According to Gere and Timoshenko (1997), load-carrying capacity (LCC) of a circular cross-section in relation to bending and torsional loads strongly depends on trunk diameter (D):

$LCC \sim D^3$

This means, wind load depends in a similar way on tree-height as load-carrying capacity on cross-sectional diameter. The breaking safety of a structure is typically described by:

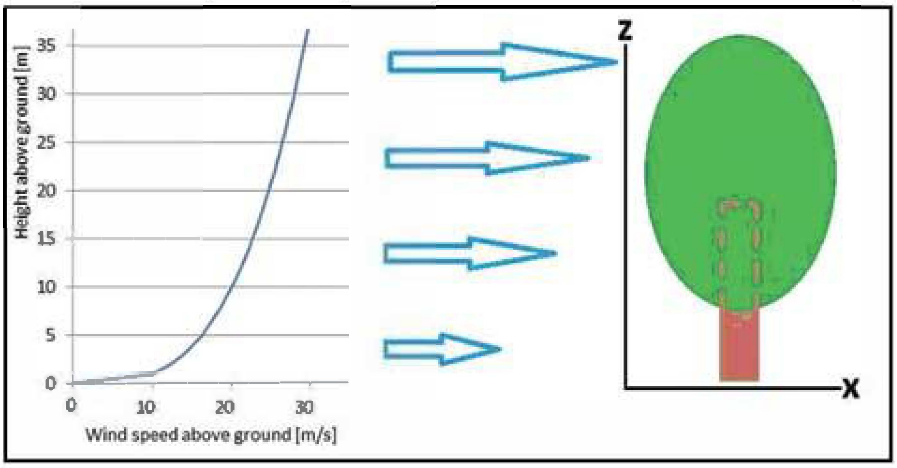
Load-carrying capacity ($\sim D^3$) / Load ($\sim H^3$).

Consequently, D^3/H^3 can be seen as a measure of breaking safety.

When H/D of trees is constant for decades as found by Kahle (et. al. 2008), D/H is constant, too. Ob-

> *...cross sectional diameter at the lower trunk largely depends on tree-height to provide constant breaking safety.*

Figure 1. Commonly, wind speed increases with height above ground, mainly depending on the so-called surface roughness, describing typical height of buildings or vegetation and characterized by a certain parameter in the equations.



viously, then D^3/H^3 is constant as well. This automatically leads to the conclusion that cross sectional diameter at the lower trunk largely depends on tree-height to provide constant breaking safety during this time period. This shows that cambial growth is not influenced locally by mechanical stress alone, but that it is also a consequence of a natural architecture to meet a specific purpose — constant stability.

Physiological reasons seem to be much less relevant in this context for explaining radial stem growth for this phase of tree growth. The ability to supply the crown with water, largely depends on the cross sectional area of the stem (Ennos 1999). The cross-sectional area of the stem increases in proportion to stem diameter to the power of two (~D^2) – thus not in the same way as the load-carrying capacity depends on D (**Fig. 2**). As a result, the connection between tree-height and stem diameter, as represented by a constant H/D ratio for several decades, seems to be mainly a consequence of mechanical loading (proportional to H^3), balanced by load-carrying capacity (proportional to D^3).

This also helps to explain the relatively small taper seen in many trees. The lever arm of the acting wind-force increases when going down the stem because the distance to the crown increases. The bending moment of any cross-section of the stem below the crown is basically the product of the total wind force multiplied by the distance of the corresponding cross-section from the crown-force center. What this means is that if we compare two cross-sections of a stem at two different heights, the bending moment of these two cross-sections differs in the same way as the lever arm length (= distance of the corresponding cross-section from crown center). When the lower cross-section has a 10% longer distance to the crown center compared to a higher cross-section, the lower cross-section has to carry a 10% larger bending moment due to wind-loading of the crown. To compensate for this 10% higher load, the lower cross-section need only be 3% larger in diameter to provide the same stability, because the load-carrying capacity of each intact cross-section depends on the diameter raised to the third power. Consequently, 3% more in diameter supplies approximately 10% more load-carrying capacity. This explains why trees do not need to be proportionally bigger in diameter when going down the stem. And thus explains the typical taper pattern found in trees.

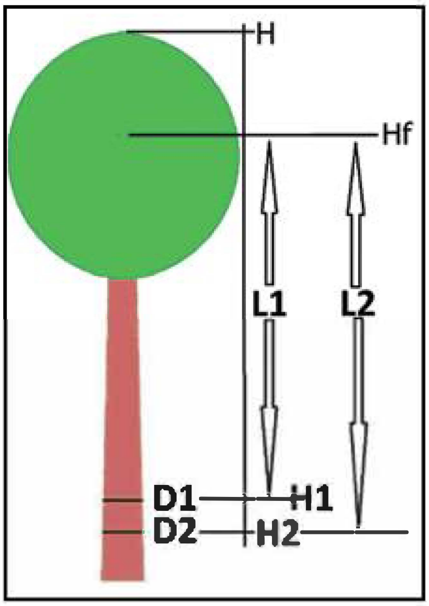


Figure 2. The difference in cross-sectional diameter between two positions at the lower stem help understand basic principles of taper: if the distance to the crown center of the lower point (L2) is 10% bigger than the distance of the higher point (L1), the lever arm of the acting wind load and thus the resulting bending moment is 10% bigger, too. In order to compensate this, it is sufficient, when the stem diameter D2 is only ~3% bigger than D1, because then D2 provides the same load carrying capacity (and breaking safety!).

The fact that wind load seems to be proportional to tree height to the power of about three may be related to the time shift between facing increased wind loads (due to height growth or changing wind pattern) and the corresponding growth response of the cambium (which requires time and can only happen during the following vegetation period). The details of this connection shall be analyzed by future scientific studies.

Understanding these relationships and growth principles helps in tree-risk assessment both in forest stands and urban landscapes.

Arboricultural consequences

Tree-risk assessors need to understand that:

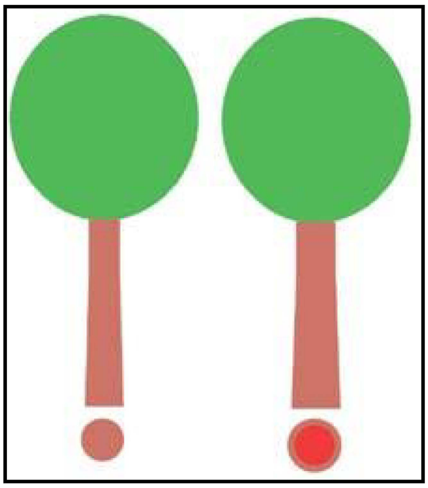
- before (conifers and broad leaf) trees reach their maximum height, the same safety measures and thresholds should be applied when evaluating breaking safety of the stem;
- after reaching maximum height, basic stem breaking safety increases with every year because load-carrying capacity increases with every annual increment.

Arborists need to take into account that wind load remains relatively unchanged when evaluating risk potential of mature urban trees that have reached their maximum potential height. Radial growth, however, continues as long as the tree is alive, and this leads to a steadily increasing stem diameter with age. Due to the proportionality of cross-sectional load-carrying capacity to diameter raised to the third power, a 1% increase of diameter leads to approximately a 3% increase in breaking safety.

Consequently, the basic breaking safety factor (proportional to D^3/H^3) then steadily increases with every additional year. Thus, safety thresholds, such as the required shell-wall-to-radius-ratio have to be adapted continually (depending on tree-age, tree-height, and annual radial increments).

The so-called ⅓-rule which states that shell-wall thickness (t) over radius (R) shall be greater than one-third for acceptable stability is valid as a safety threshold only for the time-period when both tree-height and stem-diameter are increasing and

Figure 3. Although it may sound contradictory, these two cross-sections provide the same load carrying capacity and the same breaking safety. These cross-sectional stability calculations originally have been developed for the patent on sonic tomography (Rinn 1999) and based on established mathematical basics (Gere and Timoshenko 1997). This was later confirmed by recent studies on failure modes of tubular plant organs (Spatz and Niklas 2013), such as hollow tree trunks. Spatz and Niklas showed that these conventional calculations of section modulus come to a limit when the ratio of outer intact shell-wall thickness to radius drops far below $1/5$, mainly depending on the longitudinal extension of the damage increases. The software TuboCalc™, running on WINDOWS and MacOS, allows experienced experts to practically apply the findings of Spatz and Niklas in order to analyze the behavior of even extremely hollow/damaged organic structures, such as hollow trees, under (wind) load.



providing a nearly constant H/D as described above. After having reached maximum tree-height, the required shell-wall-to-radius-ratio falls with every radial increment. In many cases, $t/R = 1/5$ or even $1/10$ can be sufficient, and can provide the same safety as the completely intact cross-section years before.

If, for example, breast height diameter (D) increased by 25% from 1m (~40 inches) at the time when maximum tree height was reached, to 1.25m (~50 inches) at a later point in time, the basic safety factor will have increased by about 95%! Therefore, the tree has nearly doubled its breaking safety compared to that when maximum height was reached. Now, if the stem of this tree has lost 75% of its core wood due to a central decay, load-carrying capacity will have been reduced by about 30%. Surprisingly, in such a tree, this deterioration still leaves approximately 35% more breaking safety than the tree had when its cross section was intact at the time it had reached its maximum height (**Fig. 3**).

Although it sounds counter-intuitive, this explains why so many mature trees that are extensively decayed internally, or that have large open cavities can withstand repeated storms. And it makes clear that evaluating mature trees requires an individual approach – because, even with significant decay, such trees can be more stable than younger and completely intact trees. Thus, before recommending pruning, topping or felling, tree-risk assessors should determine the major parameters (tree height, diameter, location and extent of internal decay, number of years and amount of radial growth produced after maximum height was reached). These measures need only be determined with reasonable precision, bearing in mind how imprecisions influence the later outcome of calculations (Rinn 2014). There is a software application available for desktop and mobile computers ('ArboStApp') that provides a comparative evaluation of critical parameters for instantly calculating loads and load-carrying capacity at the site. In this manner, a more comprehensive recommendation can be made about what should be done in order to achieve sufficient safety.

In most cases, the application of the findings presented here lead to drastically less pruning recommendations. Thus, more trees can be retained or pruned less extensively, providing increased environmental, social and cultural benefits. In addition, it can reduce costs without significantly increasing risk.

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Literature:

Buba, T. 2013: Relationships between stem diameter at breast height (DBH), tree height, crown length, and crown ratio of *Vitellaria paradoxa* C.F. Gaertn in the Nigerian Guinea Savanna. *African Journal of Biotechnology*. Vol. 12(22), pp. 3441-3446, 29 May, 2013. DOI: 10.5897/AJB12.463. ISSN 1684-5315 ©2013 Academic Journals.

Davenport, A.G. (1963): *The relationship of wind structure to wind loading. International Conference on the Wind Effects on Buildings and Structures*. pp. 26-28 June 1963, National Physical Laboratory, Teddington, Middlesex, England. (Ch. 2).

Ennos, A. (1999): The aerodynamics and hydrodynamics of plants. *Journal of Experimental Biology* 202:3281-3284.

Gere, J. M. and Timoshenko, S. P. (1997): Mechanics of Materials. PWS Publishing Company.

Hasenauer, H., Monserud, R. A. (1996): A crown model for Austrian forests. *For. Ecol. Manage.*, 84, 49-60.

Hasenauer, H. (1997): Dimensional relationships of open-grown trees. *Austria. For. Ecol. Manage* 96(3):197–206.

Kahle, H.-P., H. Spiecker, R. Unseld, P.J. Pérez Martínez, J. Prietzel, K.H. Mellert, R. Straussberger, K.E. Rehfuess (2008): *Temporal trends and spatial patterns of height growth changes in relation to changes in air temperature and precipitation, and in relation to levels of foliar nitrogen and nitrogen deposition. In: Causes and Consequences of Forest Growth Trends in Europe - Results of the Recognition Project*, Chapter: 4.2, Publisher: Brill, Editors: Kahle, H.P.; Karjalainen, T.; Schuck, A.; Ågren, G.I.; Kellomäki, S.; Mellert, K.H.; Prietzel, J.; Rehfuess, K.E.; Spiecker, H, pp.127-167.

Kalliovirta, J., Tokola, T. 2005: Functions for estimating stem diameter and tree age using tree height, crown width and existing stand database information. *Silva Fennica* 39(2), pp: 227-248.

Loehle, C. (1986): Phototropism of whole trees: effects of habitat and growth form. *American Midland Naturalist,* Jul. 1986, Vol. 116, Issue 1, p190.

Niklas, K. J., Spatz, H.-C. (2012): *Plant Physics,* Univ. of Chicago Press. ISBN-10: 0226586324.

Picard N., Saint-André L., Henry M. (2012): *Manual for building tree volume and biomass allometric equations: from field measurement to prediction.* Food and Agricultural Organization of the United Nations, Rome, and Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Montpellier.

Rinn, F. 1999: Device for investigation materials. US-Patent US6813948; international Patent PCT/DE00/01467 (1999.05.11).

Rinn, F. 2014: How much crown pruning is needed for a specific wind-load reduction? WesternArborist Spring 2014, 10-13.

Rinn, F. 2014: Error calculation in tree inspection — You've got to be kidding! *Western Arborist*, Summer 2014, 36-38.

Ruck, B. (1987): "Flow Characteristics around Coniferous Trees", *Proc. of the Second International Conference on Laser Anemometry*, Glasgow, Scotland, 131-139.

Spatz, H.-Ch.; Niklas, K.J. 2013: Modes of failure in tubular plant organs. *Am. f. Bot.* Feb. 2013.

Telewski, F. W. and Jaffe M. J. (1986): Thigmomorphogenesis: Field and laboratory studies of *Abies fraseri* (Pursh) Poir, in response to wind and mechanical perturbation. *Physiologia Plantarum* 66:211-218.

Telewski, F. W. (2006): A unified hypothesis of mechanoperception in plants. *American Journal of Botany* 93(10): 1466–1476. 2006.

Van Gelder, H. A., L. Poorter and F. J. Sterck (2006): Wood mechanics, allometry, and life-history variation in a tropical rain forest tree community. *New Phytologist* Volume 171, Issue 2, pages 367–378, July 2006.