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Investigating the Effect of Weather and Seasonal Factors on Root Stability Using Dynamic Measurements

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Abstract

The dynamic tree stability assessment technique allows trees to be measured efficiently, under realistic weather conditions. In this study, the stability of four trees, including two conifers and two broad-leaved species was assessed in the Botanical Gardens of the University of Sopron, Hungary. The examined trees included Horse chestnut, Japanese zelkova, Douglas fir and Giant sequoia. Each tree was measured in various weather and seasonal conditions. Results show that the seasons affected the stability of broadleaved trees significantly, due to considerable changes in the crown surface area, while this difference was much lower in softwoods. Rainy weather loosens the topsoil, which adversely affects the stability of trees with relatively shallow roots. Lower layers take longer to saturate, and therefore trees with very deep roots are usually unaffected by the looser topsoil, while the increased weight of the top layer compacts the lower layers and improves stability, as evidenced by results measured on Sequoia. Snow accumulation on the branches increases the inertia of the tree, which imposes higher torque on the root collar, decreasing stability. In the meantime, the increased resistance offered by frozen ground stabilizes the tree, which more-or-less counterbalances this effect. A more extensive database of tree stability under different conditions is being built to allow for more comprehensive analysis of various factors, like wind direction, tree health and morphology, shading, etc.

Keywords

Tree Stability, Dynamic Stability Assessment, Safety Factor, Wind Direction, Precipitation, Foliage, Critical Wind Pressure

1. Introduction

Many factors affect the root system (soil conditions, weather, age of tree, biological factors). Root length, root angle, number of roots, and root diameter vary greatly between species. In trees, as in engineered structures, if the normal service loads create stresses that are just below the strength of the material, they have practically no strength reserve, and the smallest accident may lead to breakage. The safety factor in trees is defined as the material strength divided by the service load (Matteck et al., 1993).

Wood in trees is flexible, and behaves as neither an ideal solid nor an ideal fluid (Vogel, 1996). Trees should be able to safely withstand high winds. The safety factor is calculated relative to the high wind level typical to a geographical area (Cullen, 2002). Many studies on conifer seedlings show that root deflection in propagation containers can contribute to long-term growth problems after planting in the forest (Krasowski, 2003). Wood and most materials that come from plants are described as viscoelastic because their mechanical behaviour contains both elastic and viscous elements (Miller, 2005). These properties result in nonlinear behavior. Evidence of the influence of tree architecture on wind firmness has also been shown by Fourcaud et al. (1999) who carried out mechanical studies on two rubber tree clones that had similar wood properties but dissimilar crown structures (Cilas et al., 2004). The shape and structure of trees have an important impact on their mechanical stability under dynamic loading. As trees grow, the added biomass translates into greater dead weight, and the upper parts of the tree are exposed to higher wind speeds, creating larger bending moments at its base (Niklas & Spatz, 2000).

Yang et al. (2016) explored the influence of root moisture content on tensile resistance and strength with different root diameters and for different tree species. The results showed that root moisture content affected the tensile properties. A slight loss of root moisture content could enhance tensile strength, but too much loss of water resulted in weaker capacity for root elongation with tensile resistance. The main factors contributing to slope stability include soil shear strength, soil-root interactions, the quantity and distribution of roots, as well as root tensile properties (Genet et al., 2005).

Several ways exist for measuring root stability. One of them is the pulling test, which has about 25 years of background in Germany (Wessolly & Erb, 2016). More recently, a dynamic method was developed that could take advantage of actual wind loading, despite the chaotic relationship between momentary wind intensity and inclination (Bejo, Divos, & Fathi, 2017).

The aim of this study is to investigate the parameters that affect the stability of the trees. In this study, mostly external parameters, like seasonal effects, precipitation and wind direction are considered. Some of the intrinsic characteristics (like crown shape and root structure) are also considered in the interpretation of the results.

2. Factors Influencing Tree Stability

There are many factors that influence tree stability (i.e. the tree's resistance against uprooting). Some of these, like crown shape and surface area, age, etc. are intrinsic properties of the tree, and are partly taken into consideration when assessing the stability of the trees. There are also external factors that impact the stability significantly. The most important of these factors are discussed in this chapter.

2.1. Seasonality

In temperate climates, the seasons affect the growth, metabolism and general activity of trees. This also influences the stability of trees in several different ways, as follows:

1) Foliage changes

The changing of the seasons has a major effect on the foliage of broadleaved species. This also has a major impact on tree stability, since leaves significantly increase the crown surface, and transfer much of the wind loads to the system of twigs and branches, and eventually, through the crown, to the root system. This means that winds of the same intensity will impose much higher loads on the crown (and therefore much higher torque on the root collar) in the summer, when peak foliage is present, then in the winter, when leaves are absent.

In conifers, this effect is much less pronounced, or may be all together absent, since their crown surface area does not change dramatically in the winter (except for some rare exceptions, like larch, which sheds its nedles in the winter.

2) Biological activity

In general, trees are biologically much more active in the spring and summer, and tend to decrease their activity, and eventually go dormant in the winter. This affects the root system, which tends to swell and be more firmly anchored in the soil in the spring and summer, due to the increased sap flow, and become somewhat looser in the autumn and winter. This affects the stability of all trees adversely, albeit not nearly as strong as the foliage change in broadleaved trees.

3) Other seasonal factors

Seasonal changes also affect tree stability through changes in temperature. Particularly, the frozen soil in the winter may become much more resistant against uprooting, which will positively influence the stability of the tree. The nature of precipitation also tends to change in the winter, but this will be discussed in the next chapter.

2.2. Precipitation

Precipitation will also affect the stability of trees. The effect is markedly different depending on the form of precipitation.

1) Rain

Rainy weather—especially when it's prolonged—affects both the tree and the soil. Rain-covered foliage will have a somewhat increased inertia, but the effect is much more pronounced in the soil. Rainwater penetrates the ground, and loosens the soil, which will therefore allow more movement, and become less resistant to uprooting. Both of these effects will act towards decreasing tree stability.

2) Snow

Snow will also tend to decrease tree stability, but through a different mechanism. Snow will not penetrate and loosen the soil. Instead, it will accumulate on the branches (and, in the case of conifers, needles) of the tree. Sometimes the accumulation can be quite significant, and the weight of the snow will considerably increase the inertia forces, when the tree is moved by wind, and will therefore lead to increased loads. The weight of the snow will also push the tree into the ground and help anchor it, which will alleviate the increased loading to a certain extent. Nevertheless, snow loads tend to decrease tree stability, although not as much as the seasonal foliage changes (Sleet will also have a similar effect).

2.3. Wind Direction

The wind direction in most locations is not completely random. Each geographical area will have a so-called prevailing wind direction, i.e. the point of the compass where the wind most frequently blows from. During its development, this is the wind that the tree most frequently experiences, and therefore this is the direction in which it will develop the highest resistance against breakage and uprooting.

This means that the tree will be able to withstand higher loads in the prevailing wind direction, than in cross winds, where even lower winds may cause more damage.

3. Materials and Methods

4 trees of various species (*Aesculus Hippocastanum*, *Zelkova serrata*, *Sequoiaendron giganteum* and *Pseudotsuga menziesii*) were chosen from the botanical garden of the University of Sopron, Hungary (47˚40'47.2"N, 16˚34'30.4"E). The examined species include two conifers and two broadleaved species, with different morphological characteristics and root structures, to represent a wide range of the important tree characteristics. Each tree was measured three times, in different weather and seasonal conditions: in the autumn or winter when the broadleaved trees lose their leaves, in the spring, when the crown surface increases, and once in snowy or rainy conditions (for the exact measurement dates and conditions, see Table 1 and Table 2). Measurements lasted for 10 - 24 h in each case, under wind velocities of < 25 km/h. (Wind speed and duration were governed by largely unpredictable weather conditions, which unfortunately introduced a high degree of variability in these parameters). Wind measurement was monitored in one central place (on top of the NRRC building of the University), while tree inclination was measured and recorded on several trees located within 300 metres from the anemometer at the same time, for several hours at a time.

Tree inclination and wind velocity were measured by the DynaRoot system (Fakopp Ltd., 2018). The DynaRoot System has 3 main components: Anemometer, high sensitivity dual-axis inclinometer and evaluation software. Measured

Table 1. Measurement conditions and results for broadleaved species.

Species	Date	Season	Weather	p_{crit} (Pa)	Wind direction (˚)	Correl. coeff.	Safety factor	SF error
Aesculus Hippocastanum	2017-04-25	Spring	Dry	8234	45	83	9.6	2.13
	2017-11-04	Autumn	Dry	11744	152	90	14.12	2.8
	2017-11-20	Autumn	Rainy	6456	319	84	6.69	2.06
Zelkova serrata	2018-02-08	Spring	Dry	3361	158	82	3.58	0.84
	2017-10-23	Autumn	Dry	4379	337	52	5.19	1.1
	2018-04-11	Winter	Snowy	4036	329	86	4.92	0.92

Table 2. Measurement conditions and results of conifers.

Species	Date	Season	Weather	p_{crit} (Pa)	Wind direction (˚)	Correl. coeff.	Safety factor	SF error
Sequoiaendron giganteum	2017-04-20	Spring	Dry	4971	306	89	6.08	1.1
	2017-11-18	Autumn	Dry	5571	333	83	6.5	1.4
	2017-11-20	Autumn	Rainy	7118	315	93	8.56	1.7
Pseudotsuga menziesii	2018-04-01	Early spring	Dry	2379	313	94	2.92	0.53
	2018-03-14	Winter	Dry	2822	331	98	3.84	0.36
	2018-03-01	Winter	Snow	2692	134	85	2.99	0.77

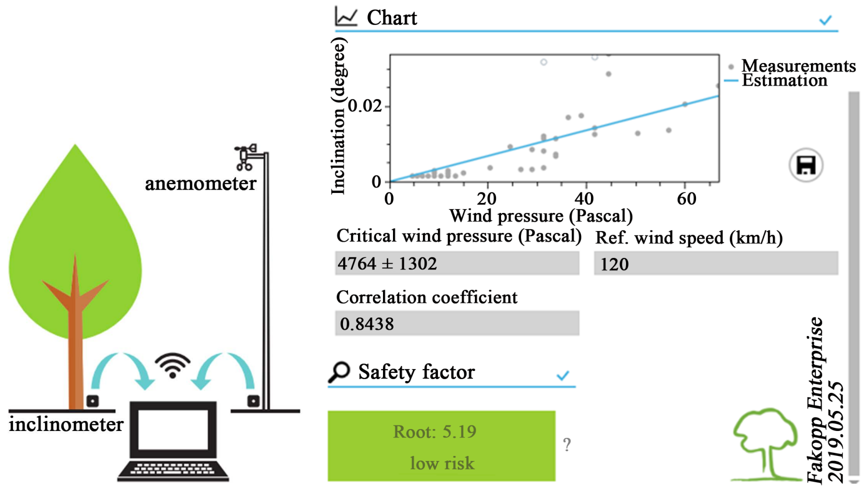
velocty and inclination data was transferred into the DynaRoot Evaluation software (**Figure 1(a)**), which estimated the critical wind pressure based on the statistical parameters of the data sets in 5-minute batches. The evaluation software calculated the Safety Factor for a critical wind velocity value (V_{wind} = 33 m/s) and air density, (ρ_{air} = 1.2 kg/m^3), as follows:

$$P_{wind} = \frac{\rho_{air}}{2} V_{wind}^2 \tag{1}$$

$$SF = \frac{M_{crit}}{M_{wind}} = \frac{P_{crit}}{P_{wind}} \tag{2}$$

where M_{wind} and M_{crit} are the torque belonging to the chosen wind velocity and the critical torque expected to uproot the tree, respectively. In the Dynaroot system, these are replaced by P_{wind} and P_{crit}, i.e. the reference and critical wind pressures, calculated from Equation (1) and estimated from the load-inclination curve, respectively. The load-inclination curve follows a special second order tangential relationship, which is extrapolated to determine the critical wind pressure. If the safety factor is lower than 1, the tree is unsafe, between 1 and 1.5 its safety is uncertain, and above 1.5 it is safe at the reference wind pressure level (i.e. at a wind speed of 33 m/s).

For more detailed information on the dynamic measurement (see Bejo, Divos, & Fathi, 2017). **Figure 1(b)** shows a sample output from the DynaRoot evaluation software.



(a) (b)

Figure 1. Schematic of DynaRoot system (a) and the output from the software (b).

4. Results and Discussion

The Safety Factor, critical wind pressure, wind direction, as well as the correlation coefficient were obtained from the measurement data. The comparison of the different trees and conditions was primarily based on the Safety Factor. Other parameters—like the SF error or the correlation coefficient were taken into consideration to refine the results.

All safety factor values exceeded 1.5 (i.e. the trees were safe in all measurement conditions), but there was significant variation depending on the season and weather conditions, due to various factors that are explained in the analysis below.

4.1. Broadleaved Trees

The measured chestnut tree was part of a row, only partly shaded from the wind. Zelkova was also partially shaded, and had an asymmetric crown. Both trees were measured in the spring and in the autumn in dry conditions. In addition, the horse chestnut tree was measured in rain as well, while one of the measurements on Zelkova was taken when snowed in. Figure 2 and Figure 3 show the situation and the foliage of these two trees at the time of measurement, respectively.

Table 1 and Figure 4 show the measurement results. Horse chestnut's SF values show it to be a very safe tree in all conditions. It also seems to be a textbook case demonstrating the seasonal and weather effects outlined in chapter 2. The larger surface, and, consequently, the increased wind loads resulted in a lower SF value, compared to that measured in the autumn. Rainy weather also caused a dramatic drop in the SF value in the autumn, even though this was measured in the stronger, prevailing wind direction. This is probably due to the looser soil, which adversely affected the ability of the relatively shallow roots of horse chestnut to anchor the tree.

Figure 2. Horse chestnut tree in autumn (left) and spring (right).

Figure 3. Zelkova tree measured in the spring (left) and winter (right).

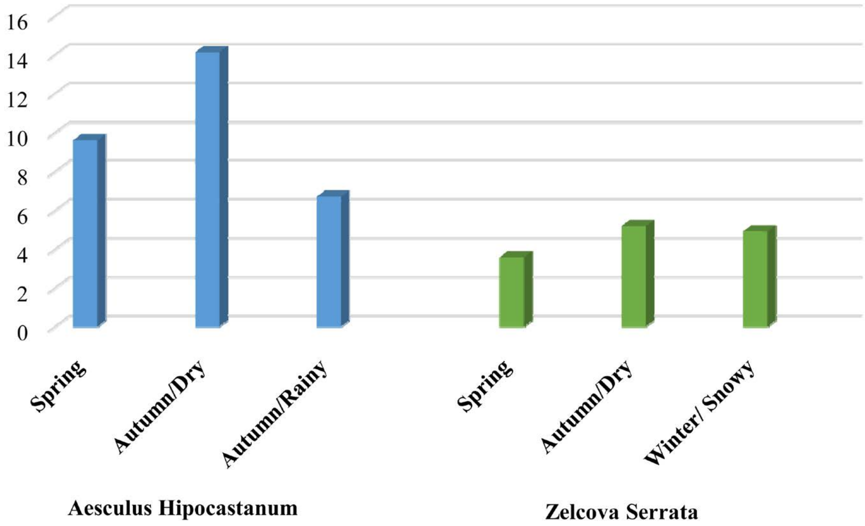


Figure 4. Safety Factor values of the measured broadleaved trees in different seasons and weather conditions.

Zelkova's Safety Factor values are markedly lower than those of horse chestnut, possibly because of the asymmetric crown, which likely exerts a higher torque on the root collar. The seasonal effect of foliage loss improved the stability of Zelkova, by approx. 50%, similarly to horse chestnut's results. Interestingly, snow loads did not significantly affect the stability of the tree. One reason may be the relatively light snow layer, as evident from **Figure 3**. In addition, frozen soil conditions may have helped stabilize the tree, counteracting the increased inertia.

4.2. Conifers

The two measured evergreens, douglas fir and sequoia, were healthy trees, partly shaded from the wind by other trees and structures. The root system depth in Douglas fir is determined primarily by the soil structure and texture. On permeable soils with favorable, moisture conditions, the roots may reach down to 60 - 100 cm, or even deeper Hermann (2005). Giant sequoia has no taproot. They only root to 3 to 4 metre deep even at maturity, but their root system covers a large area, and the dense, matted roots incorporate a lot of soil to help anchor the tree. The sequoia tree was measured in the spring and in the autumn in dry and rainy conditions. Douglas fir was measured in early spring and winter in 2 different conditions; dry and snowed in. **Table 2** shows the result of these two trees at the time of measurement, respectively.

The measurement results of coniferous trees are summarized in **Table 2** and **Figure 5**. The fact that, in sequoia's case, the wind direction varied very little, and was generally in the prevailing direction, facilitates comparision. There is less then 10% difference between the spring and autumn Safety Factors of Sequoia, which is to be expected, since there is no significant foliage change between the seasons. Autumn SF is slightly higher, even though the slowing of sap flow in the autumn should lead to shrinkage in the roots, and a slight decrease in stability, but the difference is to small too allow any meaningful conclusion in that respect.

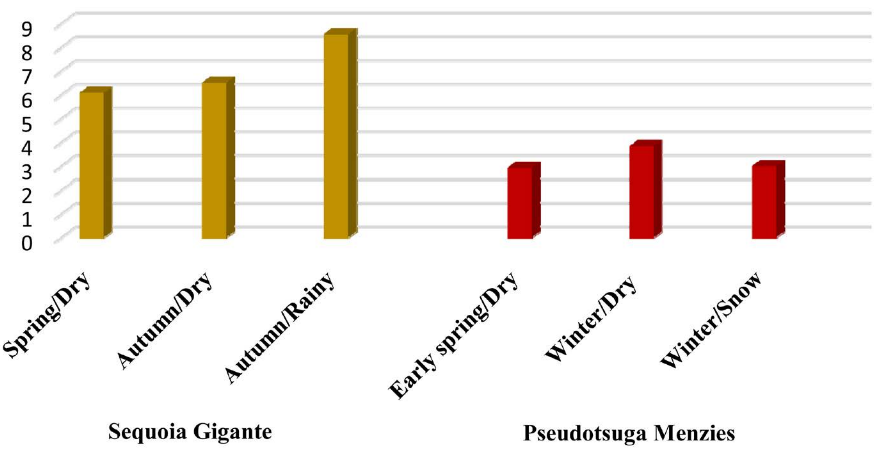


Figure 5. Safety Factor values of the measured conifers in different seasons and weather conditions.

Results measured in rainy weather on the sequoia tree completely subverted our expectations. Rainy conditions are supposed to loosen the soil, and therefore lead to decreased stability. Instead, the Safety Factor increased very significantly, by more than 40%. The explanation probably lies in sequoia's special root structure. It tends to grow a very expansive, dense, matted network of roots that incorporates a large amount of soil. In rainy weather, this soil becomes much heavier, and effectively anchors the tree even better than in dry conditions, despite the loosening of the surrounding soil. This improved the stability of the tree, and therefore the Safety Factor increased, rather than decreasing.

Douglas fir's results are more straightforward to interpret. In this case, the Safety Factor increased significantly in the winter, compared to early spring. While the foliage, did not change significantly, the frozen ground stabilized the tree in the winter (as happened in the case of Zelkova), and led to an approx. 25% increase in the SF. The accumulation of snow on the branches increased the crown's inertia and the torque on the root collar in the wind, and manifested in increased movement. This caused the Safety Factor to decrease to almost the same level as measured in the spring. Wind direction was also reversed in this instance, which may have further compromised the stability.

5. Conclusion and Future Work

The stability of four trees of various species was assessed in different seasons and weather conditions, using the dynamic tree evaluation technique. The following conclusions can be drawn based on the study:

- Foliage changes significantly affect the stability of broadleaved trees, as evidenced by the safety factor values measured on horse chestnut and Zelkova, which increased by 40% to 50% from spring to autumn or winter.
- Coniferous trees are not affected by the foliage change. Sequoia's stability was unchanged in the autumn, while Douglas fir's stability increased in the winter, most likely because of the stabilizing effect of the frozen ground.
- Rainy weather tends to loosen the soil, and therefore the stability tends to decrease. This was evident in the case of horse chestnut, whose stability decreased significantly after rain. In case of Sequoia, the safety factor increased in rainy weather. This is most likely due to sequoia's special, expansive matted root system, which incorporates large volumes of soil, which, when saturated with rainwater, provided improved anchoring and effectively increased the tree's stability.
- Snow accumulation on the branches tends to increase the inertia forces when trees move, thereby imposing more torque on the root collar, and decreasing stability. However, this is mostly counterbalanced by the stabilizing effect of frozen ground, based on our limited experience on horse chestnut and Douglas fir.

Results presented in this study are based on measuring four tree specimens in various weather and seasonal condition. The relatively low sample size allows for limited conclusions only; nevertheless meaningful inferences could be made regarding a number of factors affecting tree stability. The dynamic tree stability assessment technique allows more trees to be measured in the same time period, and a larger database is needed for a more comprehensive explanation of tree behaviour under various circumstances. Research is underway.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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