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Experimental test of non-destructive methods to assess the anchorage of urban trees

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Abstract

For risk assessment of trees in forests and urban areas an estimate of anchorage may be required. To this end, the results of non-destructive static load tests have been used for more than 20 years. Data of applied bending moments and root plate inclination are extrapolated to the point of failure in at least three ways. However, almost no studies have been published comparing estimated failure loads to measured ones. Here, we present results of almost 100 trees pulled to failure, and evaluate the accuray of non-destructive estimates.

Keywords: trees, risk assessment, anchorage, pulling test

Introduction

The failure of trees with root systems compromised by decay, storm damage or construction related damage can pose risk to significant targets and human beings in an urban setting and may also pose a risk to those involved in climbing or dismantling trees. Assessing this structural characteristic of a tree is very difficult. In many cases, when a tree is observed to have significant root issues, the recommendation is to remove the tree. This mitigates risk but also removes the stream of valuable social, environmental and economic benefits that a tree provides.

Root systems are complex subterranean structures that direct a major portion of the wind load collected by the crown into the ground. Below-ground damage to structural roots can often occur due to root decay or root severance, and may also be caused by overloading during storm events, by snow loads, or even by heavy impacts (e.g. during road accidents or avalanches).

Static load tests, as introduced by Sinn and Wessolly (WESSOLLY, 1989), can be effectively utilized to inform tree risk assessments on trees with compromised rooting stability. A tree's rooting characteristics can be assessed by applying a moderate non-destructive load with a winch, measuring the tree's reactions with a high-precision inclinometer, and extrapolating those data to determine the minimum strength of the root system (WESSOLLY, 1989; DETTER and RUST, 2013; BUZA ET AL., 2016). Estimations of resistance to uprooting are based on comparing this load capacity of the root system with modelled wind loading scenarios for a tree at its actual location, as informed by statistical wind data and local wind conditions (ESCHE ET AL., 2018).

The anchorage of trees has been studied in many scientific experiments (for an overview DAHLE ET AL., 2017) and was modelled by several authors (e.g. DUPUY ET AL., 2005; RAHARDJO ET AL., 2014). Tree uprooting is often described as a progressive failure process that occurs in different stages (O'Sullivan and Ritchie 1993), where a number of components play different roles (COUTTS, 1983). When the change in stem base inclination does not exceed 0.5° during pulling tests, the process is reversible and non-destructive (Coutts 1983; James et al. 2013).

To date, there have been no studies testing and comparing the predictive abilities of the methods used in commercial static load tests on a larger number of trees. In this paper, we compare load at failure estimated by methods published by WESSOLLY (1989) and BUZA ET AL. (2016) with load at failure measured in destructive tests.

Material and Methods

The experiments described in this paper were undertaken at several sites across Germany between 2011 and 2018. (Tab 1) summarizes the trees used and lists their average diameter and height. All trees were pulled non-destructively to 0.25° of inclination at the root plate before they were pulled to ultimate failure.

While the winching tests were underway, the applied load was measured continuously with a forcemeter (load cell) in the pulling line and the resulting root plate rotation was measured with 2 bi-axial inclinometers (one at the side of the stem base, one at the back). The instruments used are part of the TreeQinetic system (Argus Electronic GmbH, Germany). Inclinometers had a resolution of 0.001° (accuracy 0.002°) and the forcemeter had a resolution of 0.1 kN (accuracy 0.3 kN). The rope angle from the horizontal was measured either by using a digital level or data provided by the forcemeter.

The test was configured according to the Static Integrated Method or Pulling Test Method (WESSOLLY, 1989). The applied force was converted into its lateral component by the cosine of the rope angle. The bending moment was determined as the product of the lateral force component (in kN) and the lever arm length as the vertical distance from the stem base to the anchor point of the rope (in m).

The force and inclination data gathered from the non-destructive portion of those trials (up to 0.25° of inclination) was used estimated anchorage strength according to WESSOLLY and ERB (1998) (eq.1) and BUZA ET AL. (2016) (eq.2). Anchorage strength was defined as the maximum bending moment that occurred during the winching tests. We either multiplied bending moment at 0.25° with 2.5 (WESSOLLY and ERB, 1998) or fitted the formula published by BUZA ET AL. (2016) to the data measured up to 0.25° basal inclination.

$$F_{\mathrm{tilt}} = 2.5F(\phi = 0.25°) \qquad \text{eq. 1}$$

$$\phi = \frac{1}{3}\tan\frac{F}{F_{\mathrm{tilt}}} + \left(\frac{F}{F_{\mathrm{tilt}}}\right)^2 - 0.1\frac{F}{F_{\mathrm{tilt}}} \qquad \text{eq. 2}$$

Where F is force, F_{tilt} is force at failure, and Φ is root plate inclination. Data were analyzed using the statistical analysis software R (R CORE TEAM, 2018).

Table 1-Tree species and average sizes used in the experiment.

Species	n	d in cm	h in m
Betula pendula	27	40	20
Fraxinus excelsior	20	33	24
Populus sp.	19	62	29
Fagus sylvatica	10	30	25
Platanus acerifolia	9	27	18
Picea abies	2	56	27
Acer platanoides	2	32	12
Acer pseudoplatanus	1	28	27
Quercus robur	1	40	14
Tilia cordata	1	43	11

Results and Discussion

Using the method described in WESSOLLY and ERB (1998), there was a good correlation between estimated and measured anchorage strength (Fig. 1), although anchorage strenght was systematically understimated. Fitting the formula of BUZA ET AL. (2016) to the first portion of the data resulted in a poor fit and a systematic overestimation of anchorage strength (fig. 2).

(Fig. 3) demonstrates how eq. 2 fails to describe the failure process of the trees, when it is fitted to the data up to 0.25° basal inclination. When static load tests are applied in hazard tree assessment, the maximum inclination may often be even lower.

When static load tests are used to assess the safety of urban trees, it is important not to overestimate the strength of trees, because this may result in hazardous trees remaining in public areas.

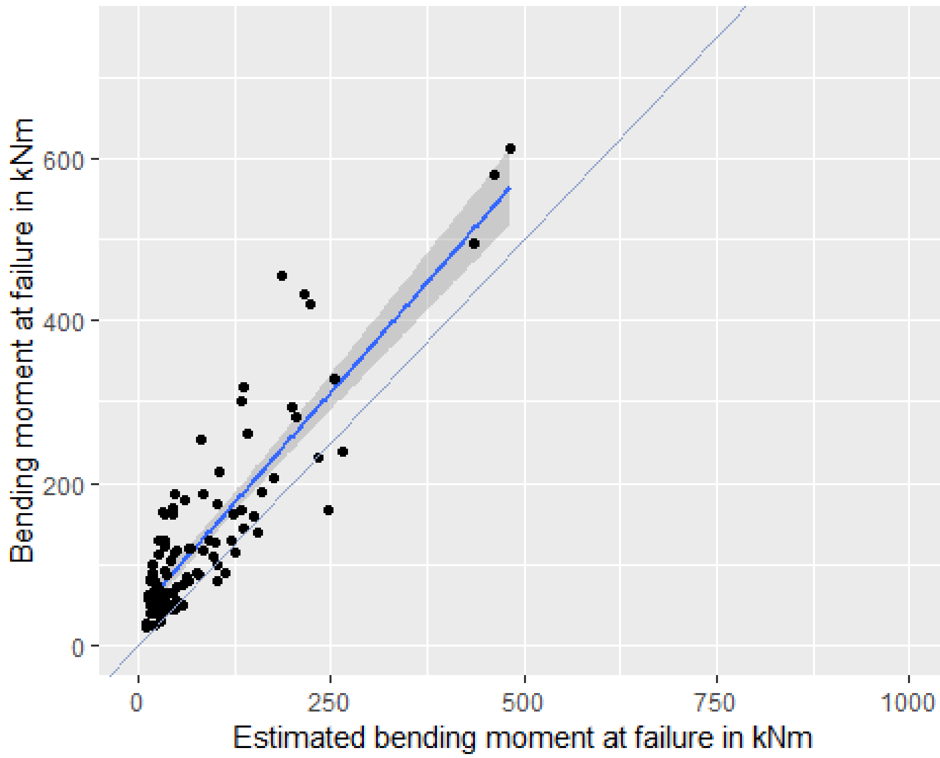

Figure 1-Correlation of estimated (WESSOLLY, 1989) and measured bending moment at failure.

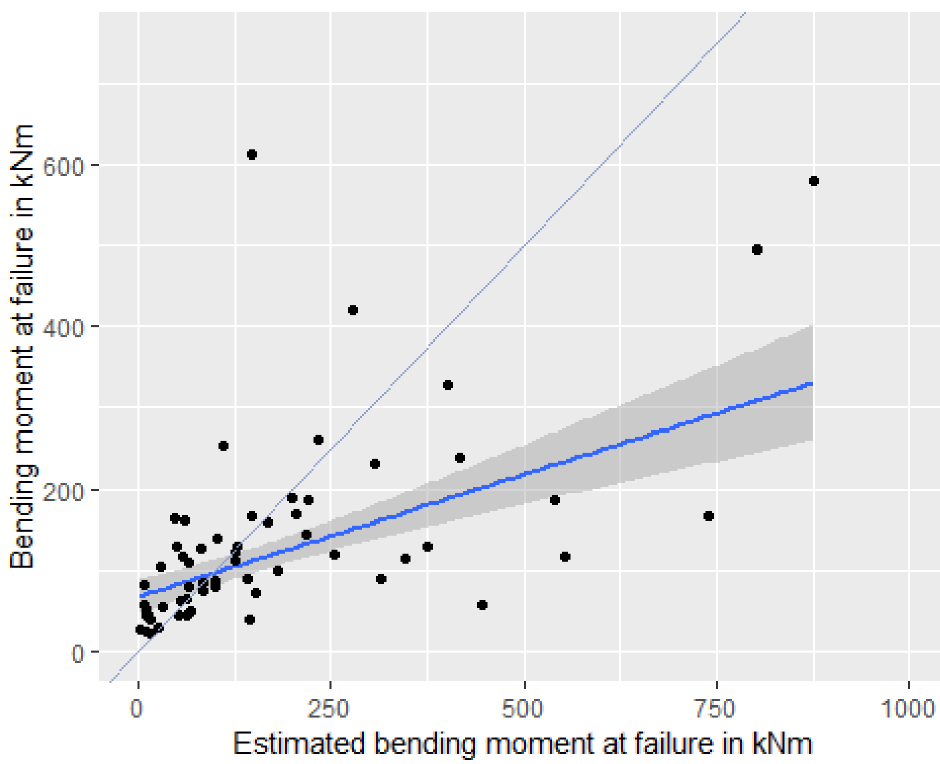

Figure 2-Correlation of estimated (BUZA ET AL., 2016) and measured bending moment at failure, compared to all data.

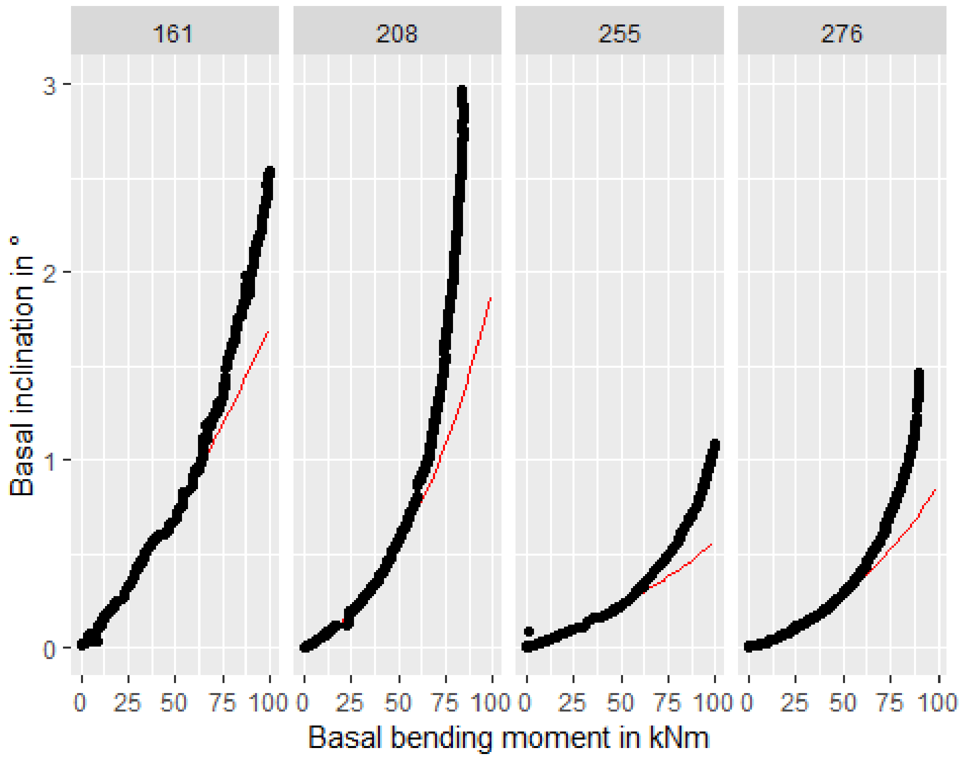

Figure 3-Fit of eq. 2 (red) to the lower part of data (0° to 0.25°), extrapolated up to true failure.

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