Urban Tree Root Stability Evaluation – Root Evaluation Based on the Trunk Inclination Baseline Shift

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Abstract

Matured and ornamental trees are important features of the landscape. Landscape architects can consider tree health during planning. To gain a clearer understanding of tree health and possible outcomes, tree root stability is an important factor to consider.

Currently, two widely accepted methods for evaluating tree root stability are the pulling test (SAG-Baumstatik SIM standard, 2024) and the dynamic root stability test (Bejo et al., 2024). While these methods are considered the most reliable for stability testing, arborists sometimes rely on a more subjective approach. While climbing or working on trees, they may sense that a tree is unsafe based on its movement. This subjective impression often proves accurate, as the tree may fail in high winds or be found unhealthy through instrumental testing. This observation suggests a potential new method for instrumental tree stability evaluation.

In experimental work, we measured the inclination changes of several trees while arborists climbed them to capture the vibrations generated during their work. Inclination sensors were placed at the root collar. The test results revealed significant differences between stable and weak trees. For stable trees, the oscillation equilibrium level—essentially the baseline inclination value around which the tree's inclination fluctuated—remained constant. In contrast, this baseline shifted suddenly when climbing an unstable tree, as noted by the arborist. The "bad feeling" described by arborists likely stems from this abrupt change in the inclination baseline. Sudden baseline shifts were also recorded in windy conditions. This behavior presents a new approach to assessing the stability and safety of urban trees.

Introduction

Trees add much value to urban life: they offer stress relaxation, provide habitat for birds and insect, shade that reduces temperature in the summer, and capture carbon dioxide and dust particles. On the other hand, urban trees often grow in adverse conditions; hard pavement inhibits rainwater absorption into the soil, traffic around the trees leads to soil compaction, and air pollution impacts growth conditions adversely (Shigo, 1986). As trees go older, worsening condition and a possible loss of stability poses dangerous risk to both property, human safety and health.

It is important to balance the important benefits of trees against the possible risk arising from tree breakage or uprooting of aging or diseased trees. Tree inspectors regularly test the condition and stability of urban trees to assess these risks. Their recommendations often include specialized, instrumented tree inspection to determine the tree's safety against breakage and/or uprooting.

There are several methods available for assessing tree safety, including single-pass sound velocity measurement, acoustic and impedance tomography, and resistance drilling. Fewer methods are available for uprooting safety assessment. Some researchers proposed techniques for root mapping based on acoustic signal conduction through the roots, but this only works for large and shallow roots, as accessing deeper roots is not possible from the surface (Buza and Divos, 2016). The standard method for uprooting safety determination is the pulling test. This approach is based on simulating horizontal loads through a concentrated load introduced through a cable, and increased gradually, while measuring tree collar inclination, which allows the determination of the ultimate uprooting torque (Wessoly and Orb, 1998).

More recently, researchers examined the possibility of measuring trees under actual wind load conditions (Kent et al. 2016, Moore and Maguire 2008, etc). While the relationship between wind intensity and tree inclination is not as straightforward as is the case of static pulling load, a statistical approach allows the evaluation of trees in a similar manner to the one used in the case of the pulling test. Earlier studies based on this approach demonstrated the principles and introduced some results and comparisons with static testing (Bejo et al. 2017, Fathi et al. 2019, 2020). Recent years has also brought several innovations that make the evaluation of the dynamic test results simpler, and the accuracy and reliability of the evaluation has improved as well (Divos et al. 2022).

Due to the paramount importance of urban tree safety, researchers keep striving for new and more reliable methods of evaluating urban trees. Even though now there are various techniques available for breakage and uprooting safety evaluation, developing new inspection methods may improve the reliability of these predictions. The purpose of the research presented in this paper is to point out a hitherto unexploited phenomenon that may provide a new approach to tree safety evaluation.

The proposed method examines the changes in baseline inclination or displacement, around which tree movement oscillates. Sudden shifts in this baseline may indicate a loss of stability arising from detrimental changes in the root system (e.g. root breakage or partial soil shear), which may ultimately lead to the tree's uprooting. Arborists often experience this phenomenon as a subjective "bad feeling" when a sudden shift occurs while climbing trees. This study presents some examples of this phenomenon as tentative results that may lead to developing a new method.

Research methods

This paper introduces four examples of different species where the baseline shift phenomenon was observed. Tree descriptions are based on Krüssmann, 1986.

1) The first investigation included two Norway spruce trees in Sopron, Hungary. *Picea abies* Karst., member of the *Pinaceae* family, is a 30-40-meter-tall tree, with a columnar and straight stam, and a regular conical crown. Its main branches curve upwards, its side branches tend to drop. The dark green needles are 4-sided, 1-2,5 cm long. Its dark brown cones are cigar-shaped, 10-16 cm long, rigid, but the scales are flexible.

   The diameter and height of the trees was 45 cm and 19 m, respectively. The trees had recently died due to woodworm infestation, but their root system was still in a relatively good condition. While an arborist was climbing the trees, their inclination was measured at heights of 0.1 m and 2.0 m in two orthogonal directions, using bubble type biaxial inclinometers, with sampling frequencies of 10 Hz and a resolution of 0.001 degree.

A mounting plate with 3 pins and a ball head were used to attach the inclinometer at the bottom of the tree trunk. The inclinometer's operating range is ± 2 degrees. The duration of the measurements was 6 mins and 10 mins, respectively. The measured inclination values were compared to the subjective experience of the arborist.

2) The second investigation involved two blue gum trees in the greater London area. *Eucalyptus globulus* Labill. is a very tall evergreen tree, growing fast to 45-55 m height. A member of Myrtaceae family. The bark is gray, persisting only at the trunk base, otherwise exfoliating in long stripes, underneath the stem is smooth, bluish-grey. The 7-15 cm long juvenile leaves are ovate to broad lanceolate, blue-green, the mature leaves are narrow-lanceolate, 10-30 cm long, pendulous, green. The white flowers are single, sometimes triple almost sessile and bloom in June-November.

   The inclination of the trees in the wind was investigated over a longer period of time, using the same kind of inclinometer mentioned before, and an ultrasonic type anemometer. The examined period included wind gust velocities in excess of 70 and 100 km/h, respectively. The first investigation included a temporary, marked change in wind direction, which effected the inclination of the tree, while the second tree had a loss of stability event due to the high winds.

3) The third example involves the movement of a Northern red oak tree in the wind. *Quercus rubra* L. is a deciduous tree with a rounded crown, reaching a height of 20-25 m and a width of 10-20 m, a member of the Fagaceae family. Its gray bark is smooth for a long time, becoming shallowly fissured when the plant is older. The very large, lobed leaves are 10-20 cm long and 7-17 cm wide, elliptical. The flowers bloom in May, they are monoecious, the male flowers are in clusters, the female flowers are single.

   Measurements took place in a small city park in Pápa, Hungary in high wind conditions (wind gust velocities up to 80 km/h), with constant southwest wind direction. Instrumentation was the same as described in example 2). A severe stability loss event was observed after the highest wind gusts, which permanently changed the inclination of the tree.

4) The fourth and final investigation involved measuring the inclination of a Colorado spruce tree in Sopron in response to wind load. *Picea pungens* is a spruce species member of the Pinaceae family growing to a height of 20-30 meters. It is a slender-broadly tree with a regular conical crown and horizontal, stiff side branches arranged in whorls. Its native habitat is the southwestern USA, in the southern Rocky Mountains. It is growing best in humid climates and good soil conditions, but tolerates drought and urban environments relatively well. Unfortunately, climate change has weakened them in recent years.

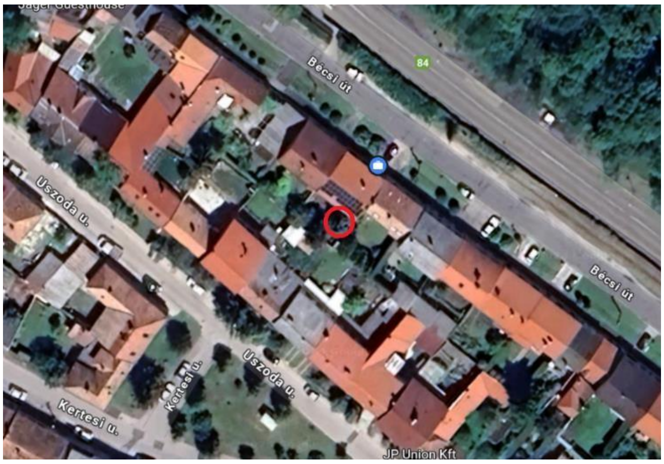

Figure 1. The location of the Colorado spruce tree measured in southerly winds. The tree is sheltered from prevailing northern winds, but is exposed from the south.

   The tree is situated very close to a house, which provides shelter from the prevailing northwest winds (see Figure 1). The measurement took place in windy weather with predominantly southern winds (ranging from SW to SE), and wind gust velocities reaching

75 km/h (22 m/s). The duration of the measurement was a little over three hours. Two distinct baseline shift events occurred during the measurement, where the oscillation equilibrium shifted, which indicates a loss of stability in the tree, possibly rendering it unsafe, which was also confirmed by dynamic Safety Factor analysis.

Results

Movement of Norway spruce while climbing

The two trees involved in the investigation showed markedly different behavior. While tree #1 showed random oscillations due to the climber's movement, the tree returned to the same equilibrium after each oscillation event, there is no baseline shift. Figure 2 shows the movement of tree #2 at a height of 2 m, while climbing. Details a and b show the movement in the X and Y directions over time, while detail c shows the movement in both directions, in both figures. The movements were similar at a height of 0.1 m, albeit less pronounced.

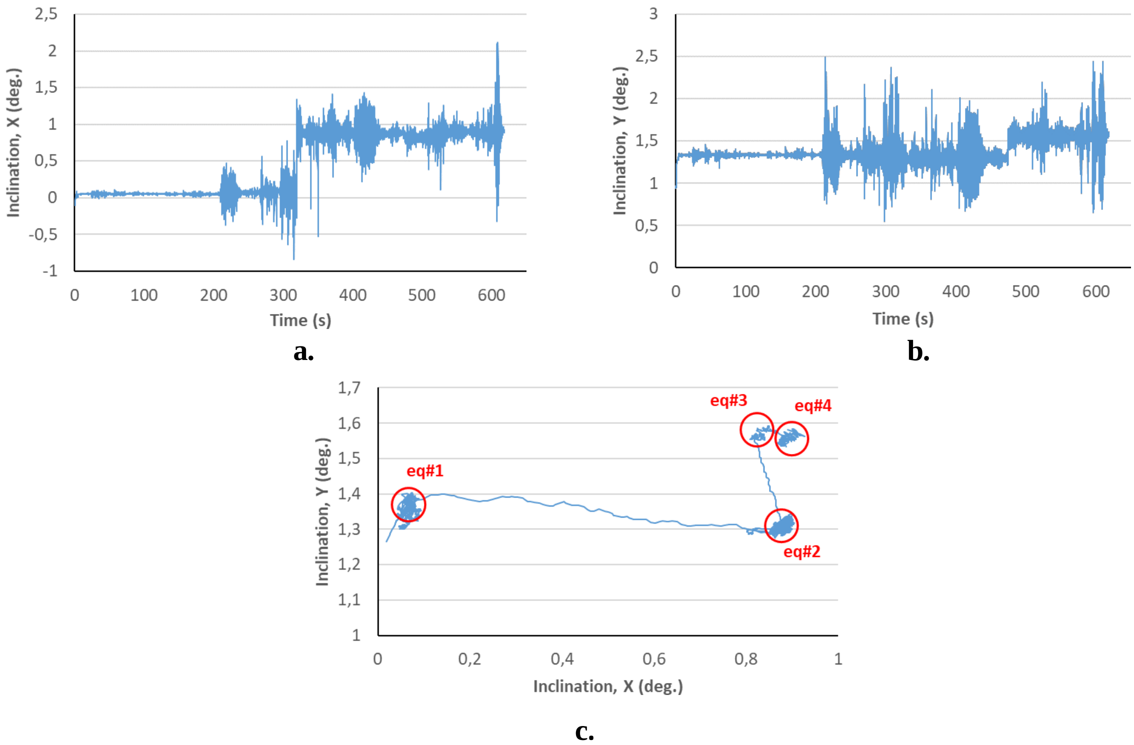

Figure 2. Inclination of Norway spruce tree #2 measured while climbing, in the X (**a**) and Y (**b**) direction, and movement in the XY plane (**c**), 10s moving average. Stability loss occurred in 3 stages (equilibrium states eq#1 through eq#4).

There are several sudden shifts in the oscillation equilibrium in Figure 2. First, there was a very significant jump at around 315 s in the X direction, from 0.05 degrees to 0.9 degrees. This was followed by another, smaller shift in the Y direction at 480 s, and another very slight shift at 525 s in the X direction again. The changes are especially striking in Figure 4c (note that the direction of the shift did not completely align with the two arbitrarily chosen axes.) These shifts were permanent; the tree did not return to its original equilibrium even after leaving the tree. The arborist reported the tree to be unsafe; the baseline shifts were evident by subjective observation as well.

Altered equilibrium positions of blue gum trees in the wind

Figures 3 and 4 shows the movement of the two examined blue gum trees in high wind conditions. The movement equilibrium state of both trees has changed due to changes in wind loading. However, there are subtle but important differences between the two loss-of-stability events.

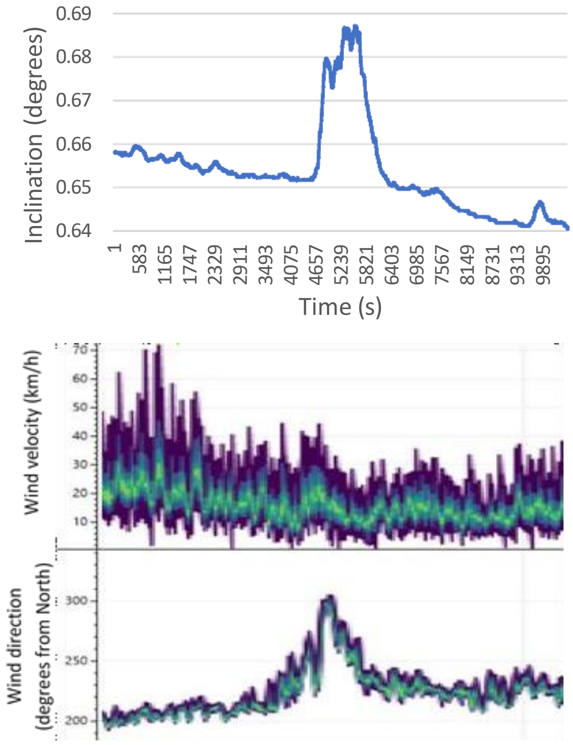

Figure 3. Inclination of Blue gum tree #1, along with wind velocity and wind direction data (in degrees from North)

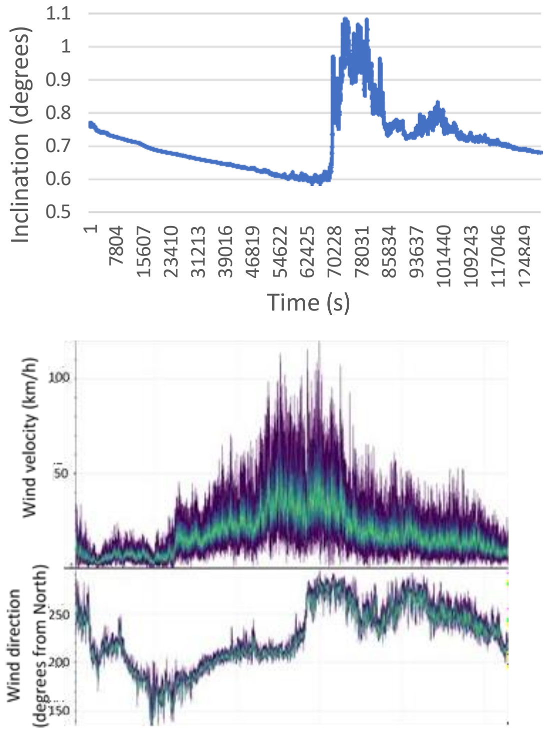

Figure 4. Inclination of Blue gum tree #2, along with wind velocity and wind direction data (in degrees from North)

Tree #1 assumed a new equilibrium state starting at approx. 4600 seconds (see Figure 3). This change was due to a relatively sudden change of wind direction from SW to NW, and the tree returned to its original equilibrium after the wind switched back to SW. The change in inclination is also relatively gradual and small (approx. 0.04 degrees). Such events do not represent permanent loss of stability, and do not signify a danger of uprooting.

Tree #2, on the other hand, showed a much faster and more drastic inclination change of approx. 0.6 degrees. Although this change also coincided in a smaller change in wind direction, the event is most likely associated with high wind conditions. Some of this change was irrecoverable, indicating a permanent shift in the equilibrium of the tree. This suggests a permanent deterioration of the root structure (either broken roots or soil shear), adversely affecting the safety of the tree.

Serious loss of stability event in red oak

Figure 5 shows the inclination of the examined red oak tree as a response to wind loading. The inclination in this diagram is shown as a 30 s moving average, thus eliminating periodic oscillations. This tree shows a very sudden, pronounced and permanent change in inclination, similar to Blue gum #2. However, in this instance there is no change in wind direction at all; the permanent loss of stability is clearly due to high winds shortly before the stability loss event, which caused permanent damage to the root plate.

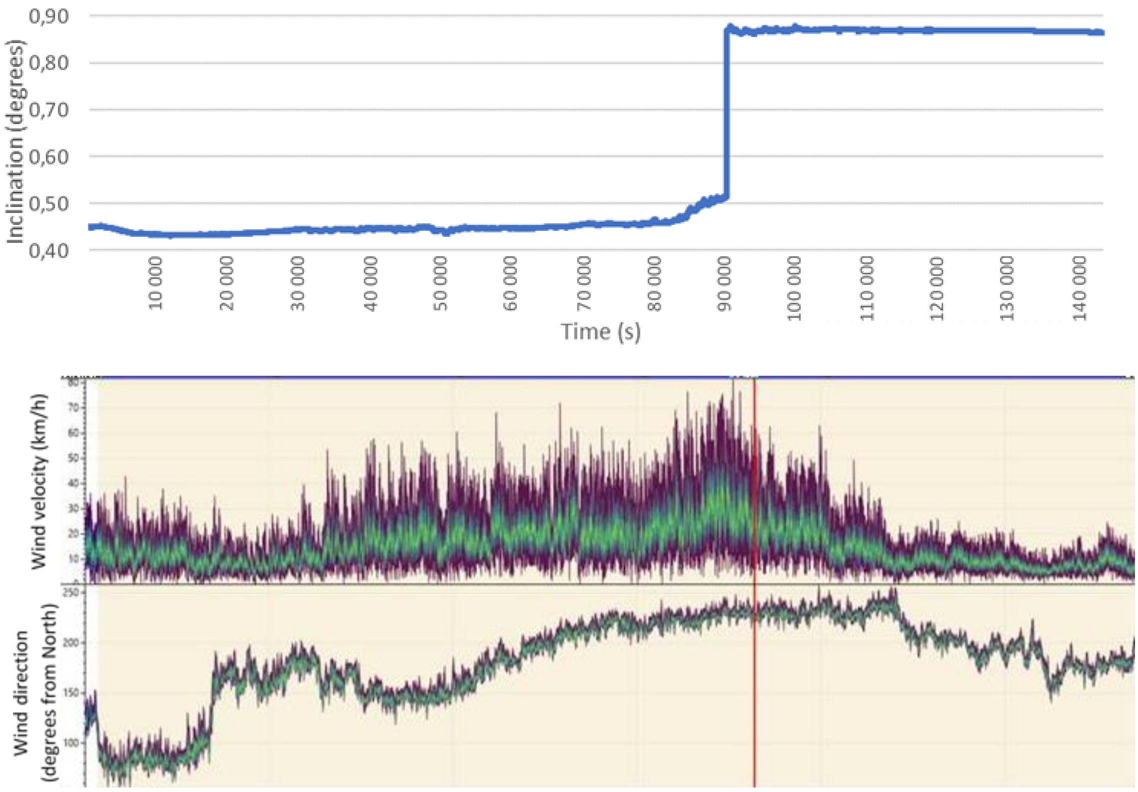

Figure 5. Permanent loss of stability in red oak, due to high wind conditions.
Inclination is shown as a 30s moving average.

Significantly, the safety factor value measured on this tree using dynamic stability testing was 1.5, which is considered safe. However, approx. 8 months after testing, the tree was uprooted, which underlines the need to augment current tree stability testing methods.

Gradual deterioration of a Colorado spruce evidenced by loss of stability

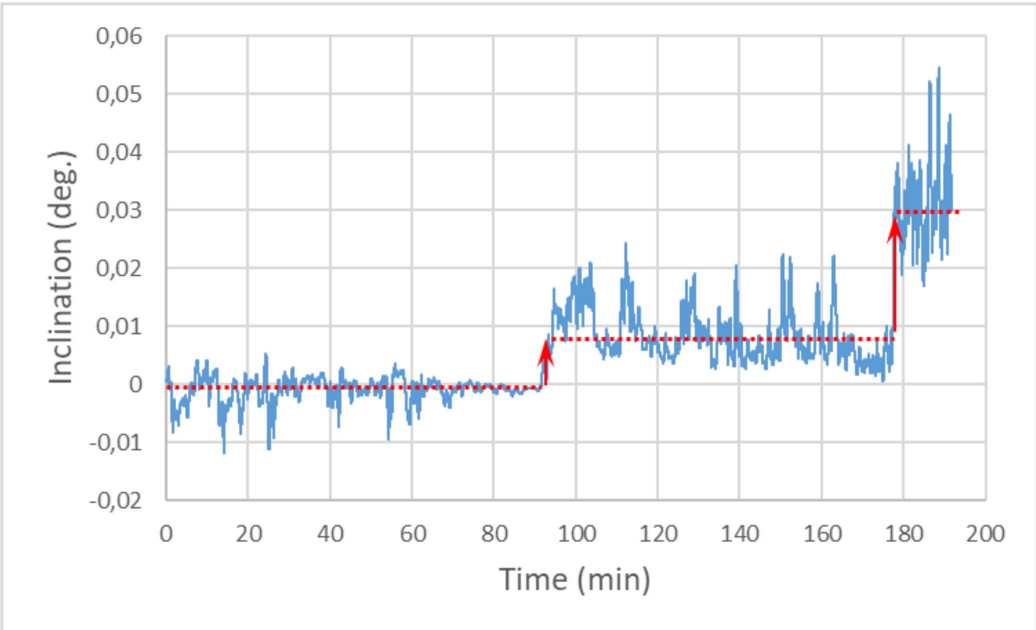

Figure 6. The inclination of an unstable Colorado spruce tree measured in windy weather.
Changes in the oscillation equilibrium are shown in red.

Figure 6 shows the inclination measured in windy weather on an unstable Colorado spruce tree in Sopron, over a 3-hour period. There are two sudden shifts in the oscillation equilibrium of the measured tree, similar to those in the previous examples, although smaller in scale. There are also more subtle, gradual changes in the baseline; these are due to changes in wind direction and intensity. These changes are smaller and more gradual than the two sudden shifts that most likely occur due to permanent and significant changes in the root system (i.e. breakage of or soil shear around some of the roots).

This tree had been monitored for its safety by measuring the dynamic Safety Factor (SF) repeatedly in various wind conditions. In prevailing northwest winds, the measurements usually resulted in relatively high SF values, ranging from 2.5 to 5. This is due to the tree being sheltered from northerly winds by the house next to it. However, in less frequent, southerly winds (similar to those at the time of this measurement), there is no shelter effect (see Figure 1). In such conditions, the SF value is much lower, typically around or below 1. This provides further confirmation that the tree may be unsafe against uprooting in southerly winds.

Discussion and conclusions

The aim of the research described in this paper was to examine the loss of stability in trees as a result of dynamic loads. Depending on the observed behavior, such events may be normal and temporary reactions to the dynamic load, or may be a sign of damage to the root system.

Trees of different species, sizes and ages were tested using various techniques, including taking measurements while climbing and during windy weather. The following conclusions can be drawn based on the collected data:

1) Small and gradual changes in inclinations tend to be the normal and temporary response of the tree to the increase in wind load, or a change in wind direction. Such changes tend to be temporary, as confirmed by the return of the tree to equilibrium after the wind subsides.
2) Sudden, more substantial changes in inclination (typically 0.5 degrees or higher) usually reveal significant damage to the root system, indicative of the deterioration in the stability and safety of the tree. Such changes may be detected and used as an early warning in the long-term monitoring of urban trees.
3) This method does not replace the established methods of stability testing, such as the pulling test or dynamic stability test, but may serve as an additional safety measure in the early detection of falling hazard.

The presented results demonstrate the potential of instrumental tree evaluation to objectively measure and quantify the balance shift felt and used by arborists to evaluate the safety of trees subjectively. This may be the first step towards developing a new technique for urban tree safety evaluation. However, significant amount of research is needed to provide further confirmation and a reliable and quantifiable method to evaluate tree safety based on this phenomenon.

The same phenomenon was also observed in Australia, where the crown movement of a Jacaranda mimosifolia tree with a very weak root system was monitored in a park in Brisbane for nearly 20 hours. During this time, the inclination consistently increased. The increase was generally gradual, but there were also 7 or 8 sudden shifts of varying intensity. The tree was uprooted at the end of the measurement, exhibiting extensive root breakage. The results also support the assumption that sudden shift in inclination baseline may be a good indicator of the root stability of urban trees. (Based on unpublished results by ENSPEC Pty Ltd, Rowville, Victoria, Australia. Research undertaken by Dr Ken James and Craig Hallam.)

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