

Static and dynamic pulling tests on a real scale tree: mechanical characterization and simplified preliminary interpretation

A.Galli¹, G. Marrazzo¹, D. Scaccabarozzi²

¹*Department of Civil and Environmental Engineering, Politecnico di Milano, Italy*

²*Department of Mechanical Engineering, Politecnico di Milano, Italy*

ABSTRACT: Understanding the complex hydro-mechanical processes governing the soil-root interactions has a pivotal role in several research areas and in particular for a relatively recent field of research concerning the assessment of the uprooting resistance of trees. The risk associated with falling trees is a newly emerging issue for risk management procedures in urbanized areas, which is also severely impacted by the ongoing climate changes. Several techniques are available for professional agronomists to assess the stability of a tree and in the last thirty years, together with other non-destructive experimental approaches, tree pulling tests have become a rather diffuse method to characterize the behaviour of a tree subjected to lateral loads. Despite such a wide use, their mechanical interpretation is still based on simplified phenomenological expressions, without considering the site environmental conditions, and limiting the analysis to simple monotonic loading paths. In the paper, the results of a more advanced loading scheme for a pulling test are presented. Test results considering cyclic quasi-static loading conditions and controlled dynamic conditions (imposed by a sudden stress release) are presented and critically interpreted on the basis of simple mechanical models. The results suggest that the governing mechanical parameters may be remarkably affected by soil conditions and SVA interaction and that simple 1dof interpreting models may not properly capture the observed behaviour.

Keywords: tree uprooting; site testing; climate conditions; tree oscillation; mechanical model

1 INTRODUCTION

In recent years, the effects of climate changes are inducing more and more frequent extreme weather events, represented by both extended drought periods and windstorms with intense rainfall. Arboreal heritage is of course particularly exposed to such phenomena, which often induce diffused tree uprooting (Figure 1 shows for example two cases of fallen trees in Milano, during a storm on July 25th, 2023). Prevention of such events and protection against sudden tree collapses is becoming an emerging issue in risk management strategies, both for forestry regions and urbanized areas. Understanding the complex hydro-mechanical processes that govern the resistance of tree root architectures against uprooting due to lateral loads is a complex and multidisciplinary task, requiring to merge agronomic, botanic and engineering competences.



Figure 1. View of fallen trees in Milano on July 23rd, 2023

Soil-Vegetation-Atmosphere interaction (SVA) evidently plays a dominant role with respect to this task, since it markedly influences not only the tree growth during its whole lifespan, but also its uprooting resistance in case of occurrence of a windstorm. Despite the noticeable amount of scientific literature on SVA for slope stability analyses (Elia e al., 2017), at Authors' knowledge the influence of SVA on tree uprooting resistance has not yet been extensively explored, with only a minor number of studies focusing e.g. on the influence of soil moisture content (see, among other works, Dèfossez et al. 2021). A deeper mechanical understanding and characterization of the tree behaviour under lateral actions would then be largely useful, both for scientific research and practical applications. Professional agronomists, in fact, often adopt the well-known pulling test scheme (see §2.2) to assess the uprooting resistance of a tree. Experimental data are then interpreted according to the procedure proposed by Wessolly and Erb (1998), which however does not consider the specific tree conditions (e.g. species, age and dimension), disregards soil properties and only considers monotonic loading conditions, thus often resulting in rather uncertain estimations (Galli et al., 2024). Dynamic monitoring of tree behaviour exposed to windy actions

is even possible (Yang et al., 2021) and simple mechanical models are employed to interpret tree sway frequencies and tilt angle records.

Starting from this background, the paper presents the results of some preliminary pulling tests performed at the testing site of the Laboratory of Analysis and Geotechnical Modelling (GeoT-LAM) at the Lecco campus of Politecnico di Milano. In particular, beyond the standard monotonic loading scheme, some advanced features have been investigated, such as the response under quasistatic cyclic loading, the dynamic response after a sudden stress release (also known as “pluck” test), the influence of the major environmental conditions. Test data have then been interpreted by using the mechanical model of a 1dof oscillator, by lumping the entire tree mass into its barycentre, to critically discuss the representativeness of this simple model.

2 EXPERIMENTAL ACTIVITY

2.1 Testing site and monitoring data

An exemplar of *Liquidambar Styraciflua* (15 years old, 11 meters height and with a trunk diameter of 23 cm at 1.3 meters above the ground) was chosen as testing tree. The estimated total weight of the tree, computed by assimilating the trunk to a regular cone and by assuming the canopy to approximately have the same weight of the trunk, is $W=6.28\text{kN}$ (assumed green weight of the wood 700 kg/m^3). The elevation of the barycentre can instead be assumed to be $2/3$ of the total height, i.e. $h_W=7.3\text{ m}$. The tree is rooted in a 50-60 cm layer of silty sand. The site is being monitored by means of one weather station (data acquired every 30 minutes) and two soil moisture measurement probes installed next to the tree at a depth of 20 cm (Figure 2). Probe 1 was connected to a continuous monitoring system (data acquired every 10 minutes), whilst for probe 2 instant soil moisture readings were manually taken.

Two testing sessions were performed, on July 2nd and August 1st, 2024, respectively. The monitoring system revealed daily temperature excursions of approximately 15°C , with an average increasing trend of $6^\circ\text{C}/\text{month}$ (Figure 3a). A relatively high solar radiation with a decreasing trend was instead measured (Figure 3b). Rainfall events are characterized by a relatively short duration (Figure 3c collects the daily cumulated rain data), with intensity values ranging between 40 and 60 mm/day, approximately once every 7-10 days. The soil moisture measurement probes for the same period show a rather complex evolution (Figure 3d; for the sake of clarity, the data of probe 1 were plotted as 7-days moving average; the calibration procedure has been here omitted for the sake of brevity). Clear peaks are present in correspondence of the rainfall events, but a general decreasing trend (drying period) in July and August is evident. After this period, an opposite increasing trend

is observed (wetting), consistently with the occurrence of major rainfall events ($>80\text{ mm/day}$) and of a decrease in outdoor temperature and solar radiation.

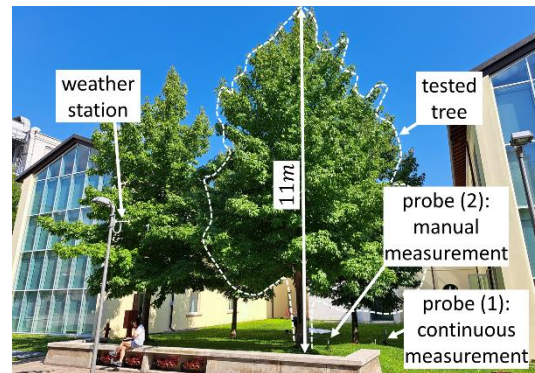


Figure 2. View of the GeoT-LAM testing site

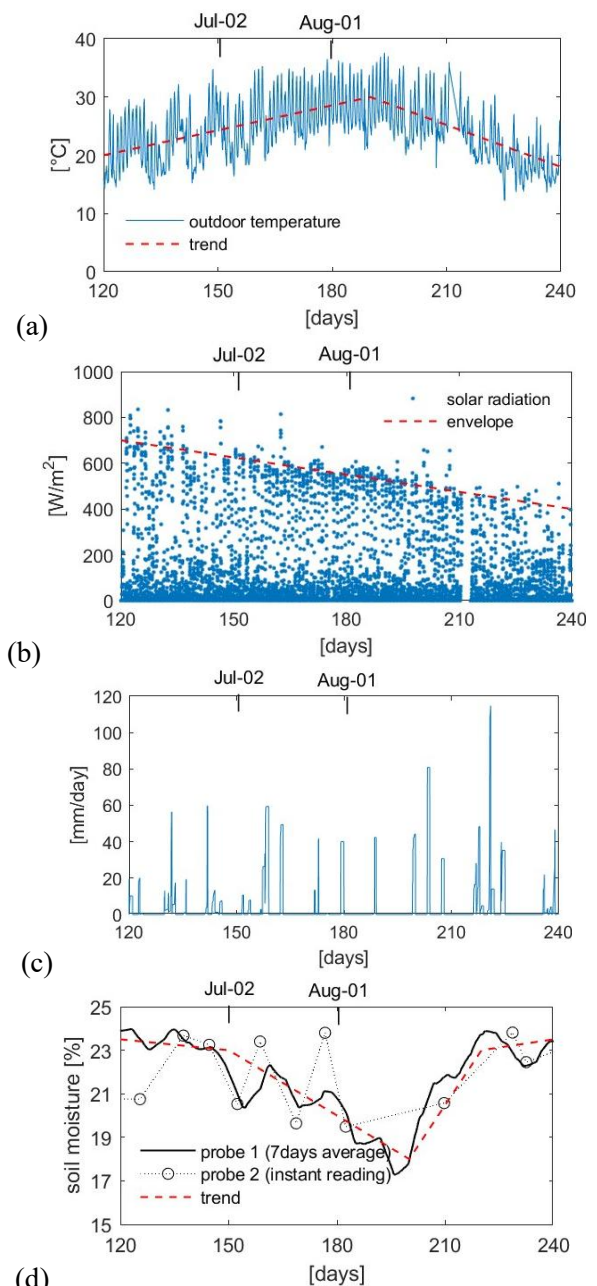


Figure 3. (a) outdoor temperature, (b) instant solar radiation, (c) daily cumulated rainfall and (d) volumetric soil moisture records at the testing site

2.2 Static tests

The loading scheme for the pulling tests is sketched in Figure 4a and it consists of applying a transversal force F to the tree stem by measuring the rotation φ at the base of the trunk. The adopted on site setup for the tested tree is shown in Figure 4b.

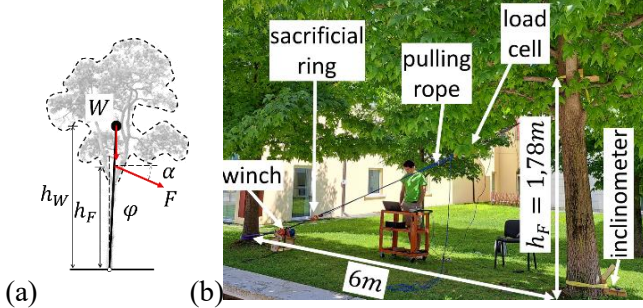


Figure 4. (a) testing scheme; (b) execution of the test

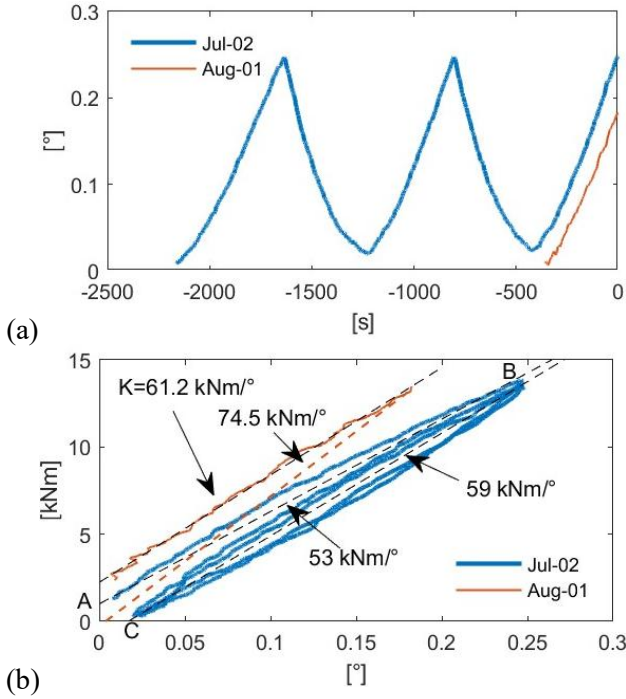


Figure 5. (a-b) loading program and moment-rotation curves of the two tests of July 2nd, and August 1st, 2024, respectively

The imposed loading histories of the two tests (before the stress release) are reported in Figure 5a: two load-unload cycles followed by a final loading phase were imposed for the test on July 2nd, and a simple monotonic loading phase for the test of August 1st (abscissae axis is expressed as time to release). According to standard agronomical practice trunk rotations were limited to 0.25°, which is considered as a safe rotation limit for the tree. The resulting moment-rotation curves are plotted in Figure 5b, together with the values of the secant rotational stiffness, labelled as K . The test of July 2nd revealed K values of about 53 kNm/° during the virgin loading phase (segment A-B) and of 59 kNm/° (i.e. +11.3%) during the cyclic phase (segment B-C). The test of August 1st shows a stiffer response, with K values

of 61.2 kNm/° and 74.5 kNm/° (+21.7%; this latter was back-estimated after stress release) during the virgin and release phases, respectively. Of course a critical understanding of these values would require a detailed characterization of the soil and root mechanical properties, of the root plate geometry and of possible damages induced to the roots (e.g. pull-out or stretching); however, the fact that the tests were repeated on the same tree (and, hence, on the same soil and the same root plate) and the observed increase in the overall stiffness values (suggesting that no evident damage was induced to the roots) make the comparison highly meaningful. In particular, the data suggest that rotational stiffness K in cycling loads (as windy loads are) may significantly differ from that characterizing a virgin loading phase, even at low rotation amplitude and that it can also rapidly evolve during the same season, apparently in meaningful accordance with soil drying periods, controlled by weather conditions and SVA interaction.

2.3 Dynamic “pluck” tests

At the end of the quasistatic loading phase a sudden stress release was induced for both tests (a sacrificial ring with limit resistance of 8 kN was used; Figure 4b). The recorded oscillations of the two tests are shown in Figure 6 (abscissae axis is here expressed as time since release); for the sake of clarity the graphs are limited to the very initial part of the record (10 seconds), whilst a view of the entire dataset (30 seconds) is reported in a upper right plot. The band of uncertainty due to data accuracy (0.0055°) is indicated as dash-dot lines. The test of July 2nd (Figure 6a) shows a quick damping down to a residual rotation value of 0.025°, with two main oscillations (peaks in points P₁ and P₂). Further oscillations beyond 10 seconds are within the instrumentation measurement uncertainty and they have been considered irrelevant. The test of August 1st (Figure 6b) shows instead no oscillations at all, with decreasing response down to a residual rotation value of 0.0037°. The data have been interpreted by means of the dynamic equilibrium equation of a 1dof rotational oscillator:

$$\frac{W \cdot h_W^2}{g} \frac{\pi}{180} \ddot{\varphi}(t) + \eta \cdot \dot{\varphi}(t) + K \cdot \varphi(t) = 0, \quad (1)$$

where the rotational moment of inertia is expressed as a function of the tree weight W and of the height h_W of its barycentre (Figure 4a), η is a viscous parameter, whereas K is the rotational stiffness. The equation can be rearranged as

$$\ddot{\varphi}(t) + 2\delta \cdot \dot{\varphi}(t) + \omega^2 \cdot \varphi(t) = 0 \quad (2)$$

where the parameters

$$\delta = \frac{180 \cdot g \cdot \eta}{2\pi \cdot W \cdot h_G^2} \quad \text{and} \quad \omega^2 = \frac{180 \cdot g \cdot K}{\pi \cdot W \cdot h_G^2} \quad (3)$$

have been introduced. Values of tree inclination and angular velocity measured at the base of the trunk just after the stress release have been imposed as initial conditions. Solutions of equation (2) depend on parameters δ and ω , and they can reproduce decreasing rotations without oscillations if $\delta = \omega$ (critical damping) is chosen or asymptotically damped oscillations if $\delta < \omega$ (subcritical damping) is assumed. The case $\delta > \omega$ (supercritical damping), was considered not to be relevant. Both analytical solutions have been implemented and fitted on the data (a least square method was adopted; details have been here omitted for the sake of brevity), and critically discussed here in the following.

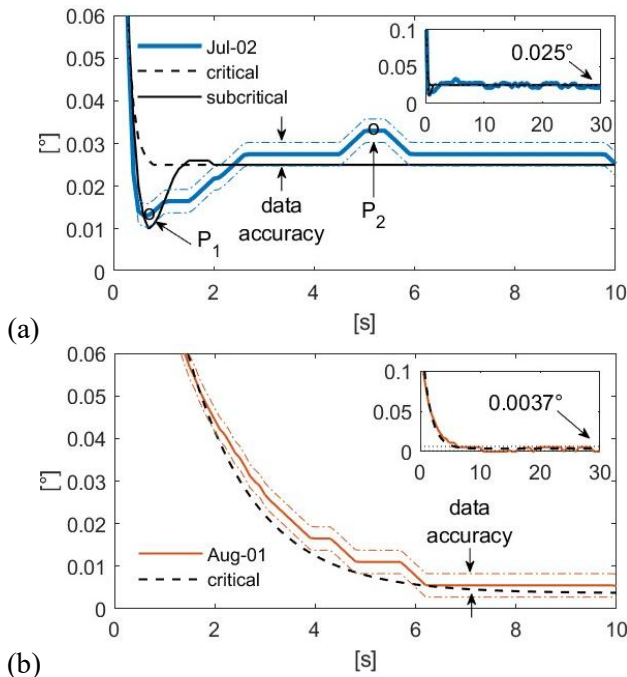


Figure 6. (a-b) release phases of the two tests of July 2nd, and August 1st, 2024, respectively

Figure 6a shows the best fitting curves for both critical and subcritical damping, respectively, for the test of July 2nd. The best fitting values for ω are 9.39 and 4.40 rad/s, for critical and subcritical cases, respectively. By applying the definition of ω given in equation (4) and by remembering the values $K = 59 \text{ kNm}/^\circ$ and $h_W = 7.3 \text{ m}$, an indirect estimation of the tree weight W can be obtained. For the critical case it corresponds to $W = 6.99 \text{ kN}$, which is in very good agreement with the previously estimated value (6.28 kN) and, being for critical damping $\delta = \omega$, a value of the viscous parameter $\eta = 8.41 \text{ kNm} \cdot \text{s}/^\circ$ can also be estimated. For the subcritical case an exaggerated value $W = 31.92 \text{ kN}$ would instead be obtained (more than four times the previously estimated one), suggesting that subcritical damping cannot be considered representative for this test. It is also evident how points P₁ and P₂ cannot be both matched by the analytical models, thus suggesting that higher oscillation modes (e.g. trunk inflection or canopy oscillation) may have been excited. As far as the

test of August 1st is concerned (Figure 6b), it clearly appears that no oscillations are present, and subcritical damping is not hence representative. If however a critical damping is assumed, the obtained value for ω (0.82 rad/s) has judged to be not significant, since it would imply an unrealistic tree weight. It can then be concluded that more complex and advanced interpreting models should be adopted, supporting their development by additional dynamic testing, aimed at measuring the dynamic response of the tree in a low frequency range, where the tree response is expected to be present.

3 CONCLUSIONS

The paper discussed the experimental results of some pulling tests on a real scale tree, both considering cyclic quasistatic and dynamic conditions. The data from cyclic tests demonstrate that the tree rotational stiffness under virgin monotonic load may markedly differ from that during unloading-reloading phases, and that it can evolve depending e.g. on weather conditions, soil drying/wetting periods, SVA interaction. The interpretation of the pluck tests (dynamic) revealed that the rotations at the base of the trunk can hardly be interpreted as a 1dof oscillating system, since contributions from higher deformation modes have been evidenced (e.g. trunk inflection or canopy oscillations). Nevertheless, provided that suitable mechanical models are adopted, the presented interpretation of the experimental data may suggest a calibration strategy for the main governing mechanical parameters (e.g. the rotational stiffness, the viscous damping or the tree weight) which can hardly otherwise be estimated in practice.

4 REFERENCES

- Défossez, P., Veylon, G., Yang, M., Bonnefond, J., Garrigou, D., Trichet, P., and Danjon, F. 2021. Impact of soil water content on the overturning resistance of young *Pinus Pinaster* in sandy soil, *Forest Ecol. Manag.* **480**, 118614.
- Elia, G., Cotecchia, F., Pedone, G., Vaunat, J., Vardon, P.J., Pereira, C., Springman, S.M., Rouainia, M., Van Esch, J., Koda, E., Josifovski, J., Nocilla, A., Askarinejad, A., Stirling, R., Helm, P., Lollino, P., Osinski, P. 2017. Numerical modelling of slope-vegetation-atmosphere interaction: an overview, *Quarterly Journal Eng. Geol. Hydrogeol.* **50**, 249–270.
- Galli, A., Sala, C., Castellanza, R. et al. 2024. Lesson learnt from static pulling tests on trees: an experimental study on toppling behaviour of complex foundations, *Acta Geotechnica* **19**, 1477–1494.
- Wessolly, L., Erb., M. 1998. *Handbuch der Baumstatik und Baumkontrolle. (Manual of tree statics and tree control). Vol. 270.* Berlin, Germany: PatzerVerlag.
- Yang, Z., Hui, K.W., Abbas, S., Zhu, R., Kwok, C.Y.T., Heo, J., Ju, S., Wong, M.S. 2021. A Review of Dynamic Tree Behaviors: Measurement Methods on Tree Sway, Tree Tilt, and Root-Plate Movement, *Forests* **12**, 379.