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A macroelement approach for the stability assessment of trees

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Abstract: Interaction diagrams in the generalized 3D loading space of vertical (V), horizontal (H) and moment (M) actions constitute the basis of the design of foundation structures in case of complex loads combinations. The mechanical response of such systems is frequently interpreted in terms of the 'macroelement' theory, where a generalized incremental constitutive relationship is introduced, linking the displacements and rotations of the foundation (playing the role of generalized strains) to the histories of applied loading components (i.e. the generalized stresses). In this paper an attempt to extend a classical macroelement framework, to the case of root-soil interaction presented. The model is calibrated on small scale experimental data on 3D printed plastic root systems, subject to combined V-H-M loads, and a parametric analysis on the main governing parameters is discussed. The comparison between numerical and experimental data suggests that the macroelement approach could be an efficient and simple analytical tool for describing the whole moment-rotation curve, overcoming the main simplifying hypotheses currently employed in arboriculture practice.

Keywords: Soil-structure interaction, roots, trees, macroelement, bearing capacity

1 Introduction

Assessing the stability of trees against combined vertical/horizontal actions and toppling moments (such as those induced by wind actions) is still a challenging problem in professional arboriculture practice, since variability in the definition of input actions and uncertainty in the characterization of the tree make any deterministic evaluation largely inaccurate. Moreover, trees are living bodies, whose growth (and senescence) induce not only an evolution in shape (i.e. an evolving geometry), but even possible remarkable changes in mechanical properties, due, for example, to the fungal development and disease. Seasonal leaves changes may even largely affect the interaction with wind gusts, thus eventually influencing the stability assessment against a prescribed wind action. Tree stability is traditionally intended with respect to trunk or branch failure due to bending and torsional actions (Figure 1a), although a large amount of failure events involves the complete toppling of the tree-root system, with the activation of an uprooting mechanism (Figure 1b).

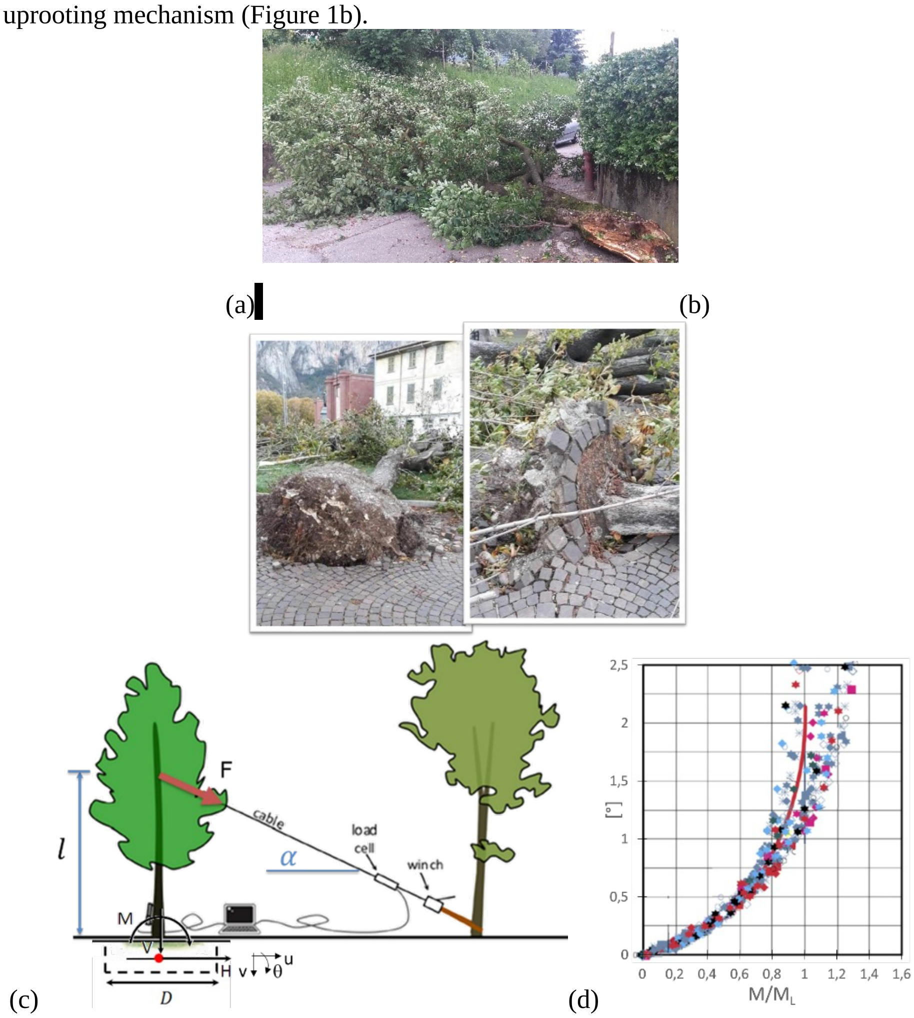


Fig. 1 Example of (a) branch failure (Oggiono, 2018) and (b) uprooting failure (Lecco, 2018; courtesy of Mrs. Marzia Fumagalli); (c) schematic view of a pulling test; (d) Wessolly interpolating curve.

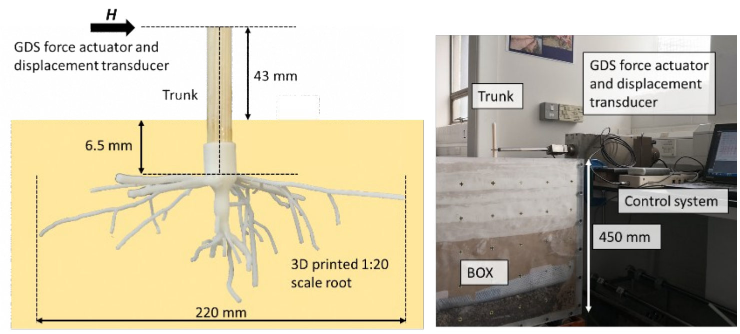
In practical application, Visual Tree Assessment procedure (VTA; Mattheck and Breloer, 1998) is widely adopted for tree inspection and symptoms recognition, although it requires high arboricultural expertise. Some quantitative geometry-based indices are also employed to check the safety against the failure of the trunk, like the ratio (ratio of the thickness of the wood wall to the radius of the trunk), the slenderness coefficient (ratio of the height of the tree to the diameter of the trunk), the wind safety factor (ratio of the trunk diameter to an equivalent lateral dimension of the tree crown), although they do not explicitly consider the amplitude of the wind loads and the wood mechanical properties. Only in recent years the Static Integrated Assessment (SIA, Wessolly and Erb, 1998) introduced the idea of studying the tree as a "natural" structure, obeying to classical equilibrium and compatibility equations, restricted by a proper failure criterion for the wooden material (further details can be found in the comprehensive book published by Sani, 2017). Trunk or branch failure, however, are out of the scope of the present work, and in the following the attention will be only focused on uprooting failure mechanisms, directly involving soil-root interaction, by assimilating the tree to a structure and the root system to its foundation. Safety against toppling failure mechanism due to wind actions is nowadays assessed by means of Static Integrated Method (SIM), consisting in the execution of non-destructive real scale static pulling tests on the tree (a schematic view of the test set up in shown in Figure 1c), where an increasing value of moment (computed by taking into account the point of application and the inclination of the tensile force) is imposed to the trees and the corresponding rotation at its base is recorded. The authors generally observed the peak uprooting resistance of the trees for rotation values of about 2-2.5°, after which the self-weight of the tree caused the complete toppling. In common stability assessment practice, tests are usually limited within a maximum value of the tilt angle =0.25°, which is considered a safe rotation limit avoiding significant damage to the roots. Following the Wessolly approach, the experimental curve is then interpreted with reference to a rich database of real scale experimental tests (about 400 pulling tests run until the complete uprooting; Figure 1d) allowing to extrapolate the value of the limit moment .

From a geotechnical point of view, pulling tests consist in imposing a combined set of horizontal (), vertical () and toppling () loads on the root system, characterized by a positive (i.e. downward oriented) vertical load component. On the other hand, actual load combinations induced by real wind gusts are rather characterized by negative (i.e. upward oriented) vertical load components, due to the sail effect of the tree crown. The above described Wessolly method actually neglects the effects of vertical load components. In the classical framework of the macroelement model for shallow foundations, however, positive or negative vertical load components are in principle expected to increase or decrease, respectively, the tree resistance against uprooting, thus making the traditional Wessolly approach potentially highly inaccurate.

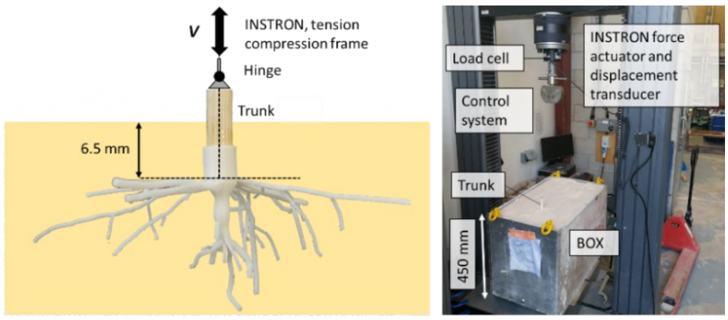
In the present paper, an attempt to interpret 1:20 scale 1g tests on 3D printed plastic root system by means of the traditional macroelement approach used to model shallow foundations is presented. A preliminary calibration strategy is also described and the results highlight the importance of considering the applied vertical load load on the .

2 Description of small scale experiments

A 900 mm × 450 mm × 450 mm box was used to contain the model soil; the size of the testing box was chosen in order to avoid boundary effects (Figure 2a,b). The soil used in this study is a mixture of dry 70% HST95 sand and 30% A50 silt, sieved in air to a relative density of approximately 48%. The obtained soil was characterized by a dry unit weight =16.5kN/m^3 and a critical state friction angle =38° derived from direct shear tests. A 1:20 scale root system model was reproduced by a 3D printer system, with a global diameter =220mm and a total weight of 0.74 N and embedded at 6.5 mm below the ground level. The root analogues were prepared following the procedures outlined in Liang et al., (2015) using ABS plastic which was found to have mechanical properties similar to real roots. Preliminary vertical tests under tension (, i.e. uplift of the tree model) and compression (, including unloading-reloading cycles) for the root system allowed to estimate a vertical pull-out resistance =-14N and a vertical bearing capacity =120N, respectively (Figure 2c).



(a)



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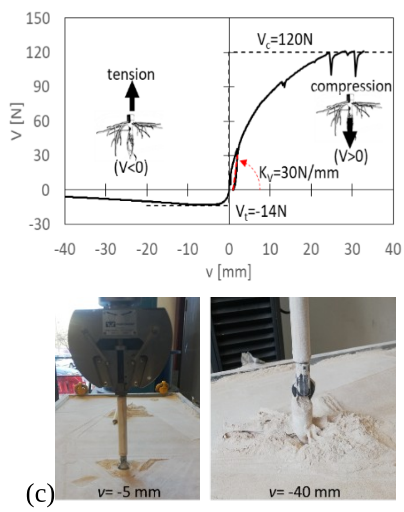
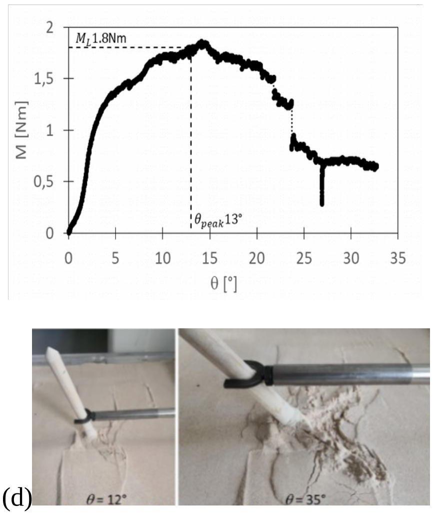


(c)



(d)

Fig. 2 Experimental set up and sketch of the 3D printed root model for the (a) pushover and (b) pull-out-compression; (c) *V-v* tension and compression experimental results including pictures for v=-5 and -40 mm and (d) M -θ lateral pushover experimental curve results including pictures for θ =12° and 35°.

The load rate for these tests was set to 0.5 mm/min and the vertical unloading-reloading cycle in the compression space showed an average stiffness of =30N/mm. Lateral push over tests (Figure 2 d), performed on virgin samples without any preliminary vertical load cycle, were run by means of a horizontal GDS force actuator applied 13 mm above ground surface, in controlled displacement condition (load rate of 2 mm/min). Force and displacement readings were logged at a sampling frequency of 1 Hz. The complete moment-rotation curve of this test showed a limit value =1.8Nm (corresponding to a limit value of the horizontal force =94.7N); a picture of the uprooting mechanism at failure is shown in Figure 2 d. Further information on the experimental set-up can be found in Zhang *et al*. (2018). After the peak, a softening phase is observed, corresponding with the progressive pull-out of the roots from the soil. It is worth noting that the small scale test is consistent with the Wessolly database, provided that the rotation values are normalized with respect to the angle , representing the rotation value corresponding with the full mobilization of the peak moment resistance (is equal to 13° for the small scale test and to about 2° in the Wessolly database). A comparison in the dimensionless plane is shown in Figure 3.

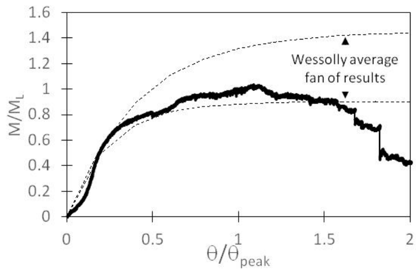


Fig. 3 Comparison between the small scale experimental results and the Wessolly database.

3 Definition of the macroelement constitutive rule

The above presented experimental results can be interpreted within the macroelement framework (Butterfield, 1980) by assimilating the model tree to a tall vertical structure, founded on an equivalent circular rigid foundation of diameter and subject to a complex loading path in the space (Figure 1c). The system undergoes the corresponding settlements along the vertical (), horizontal () and rotational () dimensions. With respect to the original version initially developed for shallow foundations by Nova and Montrasio (1991), an extended definition of the interaction domain was introduced, by taking into account both the vertical downward bearing capacity and the vertical uplift tensile strength of the foundation under centered vertical loads, respectively. Within the framework of classical isotropic strain hardening elastoplasticity, the yielding function be analytically expressed as

(1)

where parameters and govern the shape and the size of the yielding function (in the following, =0.95 will be assumed). For the sake of simplicity, normality rule is assumed and thus the plastic potential coincides with the yielding function . Generalized dimensionless stress variables are defined as follows:

(2)

with and controlling the shape of the yielding function in the space. In equations (2) parameter represents the diameter of the equivalent circular shallow foundation, corresponding with the part of the total diameter of the tree root system “contributing” to the vertical bearing capacity (see §3.1 for further information). The evolution of is controlled by the following hardening law, where is the initial stiffness of the load settlement curve under vertical centered load, and are hardening parameters describing the influence of permanent horizontal displacements and permanent rotations on , respectively:

(3)

Parameter is monotonically increasing with the plastic strains, and no softening phase can then be reproduced. Generalized strains , and are obtained as the work-conjugate kinematic variables to the generalized stress defined in equation (2), and they are related to the vertical and horizontal displacements and to the rotation, respectively. Their analytical expression is here omitted for the sake of brevity (further details in Nova and Montrasio, 1991). Failure condition is reached when =1, and the corresponding interaction domain is plotted in Figure 4.

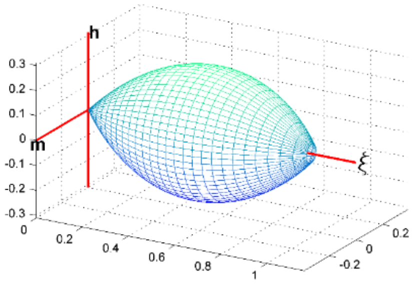


Fig. 4 Plot of the interaction domain at failure in the generalized dimensionless stress space variables.

The elastic stiffness matrix of the system can be defined according with the relationships proposed by Gazetas (1983) for circular rigid foundations on elastic half-space, where vertical (), horizontal () and rotational () stiffness values are expressed as a function of the Young modulus and of the Poisson ratio of the soil.

. (4)

3.1 *Parameter calibration and parametric analysis*

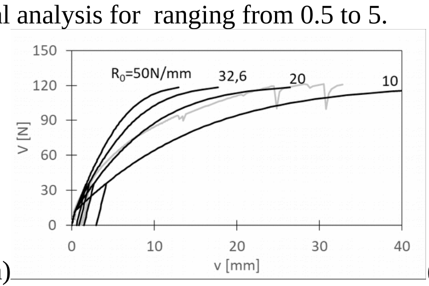
<u>Vertical compression test</u>

On the basis of the test described in Figure 2c, values and are explicitly obtained. This latter, in particular, can be analytically related to the bearing capacity of a circular shallow foundation with a diameter expressed by means of the well-known Brinch-Hansen formulation (not reported here for the sake of brevity). A back analysis on the value of can be performed in order to match the experimental value =120N. The resulting value represents a sort of “equivalent” diameter of the tree foundation, giving the part of the root system actively collaborating to the vertical bearing capacity. Such value of can be introduced in the expression of the vertical stiffness , and the equivalent value of (thought as the Young modulus of a homogenous elastic half space) can be derived by imposing the experimental value =30N/mm. Values =53mm and =514kPa are obtained. Parameter can in principle be estimated following the empirical expression suggested by Montrasio and Nova (1997), giving =32.6N/mm; such value, however, is a bit too high with respect to the experimental data, and a following parametrical analysis (Figure 5 a, where the analyses have been run by imposing an initial value =0.1 in order to qualitatively take into account the disturbing effects of the sample preparation) allowed to obtain a best fitting value =20N/mm.

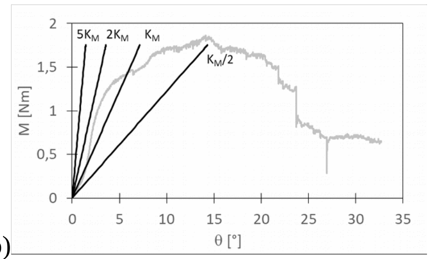
Horizontal push over test

Preliminary elastic analyses have been run in order to check the predictive capability of the elastic stiffness values defined in equation (4), in particular with reference to the rotational stiffness (tested values range from ½ to 5 time the analytical value). It has been observed (Figure 5b) that the analytical expression underestimates the experimental response about of a factor 2, meaning that the “collaborating” diameter of the root system in horizontal push over test is at least twice the value of the collaborating diameter in vertical compression test.

The plastic response of the model has then been initially investigated by running rigid plastic analyses, with the aim of calibrating (i) the failure condition and (ii) the hardening rule. It is worth noting that, consistently with the small scale experimental procedure described in §2 (Figure 2d), only horizontal tests at negligible vertical load values will be hereafter considered (and , implying a fixed value of) and the imposed loading path is then represented by a straight line at constant ratio. According to equation (1), the failure condition in the dimensionless plane at fixed value of is represented by a circle (in Figure 5c only one quarter of the circle is represented), and the inclination of the dimensionless loading path is governed by the ratio between the two shape parameters and . As a consequence, point (i) can be analytically solved by imposing to the generalized limit dimensionless stress state to belong to the failure circle for a fixed value of the ratio. In the following, in lack of further experimental tests (as it is however very common in real arboriculture practice, since only one pulling test is usually performed), an arbitrary high value =50 was introduced, in order to minimize (owing to the assumed normality rule), the amplitude of the horizontal permanent displacement of the tree. Values =3 and =150 were then obtained. The hardening rule (point (ii)) can finally be calibrated by assuming that horizontal permanent displacement should not influence the hardening parameter , i.e. =0 is imposed, whilst the parameter is optimized by fitting the experimental results. Figure 5d presents a parametrical analysis for ranging from 0.5 to 5.



(a)



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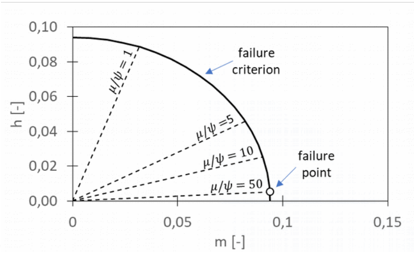

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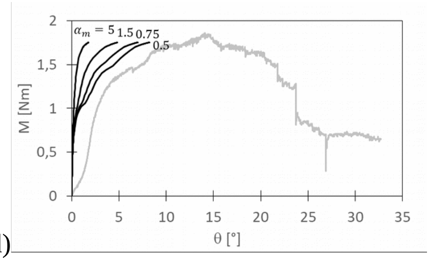
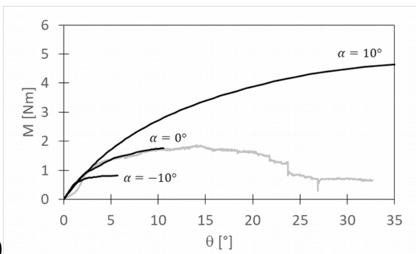


(d)

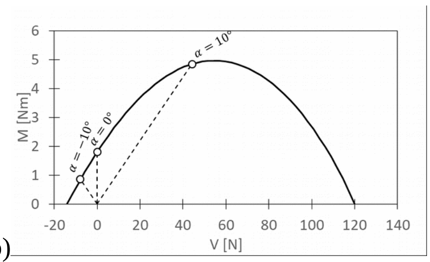
Fig. 5 (a) Numerical modelling of the vertical compression test and parametrical analysis on ; (b) elastic numerical modelling of the horizontal push over test and parametrical analysis on ; (c) influence of the ratio on the dimensionless loading path; (d) rigid-plastic numerical modelling of the horizontal push over test and parametrical analysis on . In all the plots, grey curves represent the experimental data.

3.2 Influence of the vertical load component

In this section, the influence of the vertical load component on the push over test results will be numerically investigated and compared, for the assumed interaction domain, with the purely horizontal (=0°) push over test. Two values of the inclination angle of the applied force to the horizontal will be considered =10° and =-10°, in order to qualitatively reproduce the additional downward vertical force induced by the inclination of the experimental pulling set up in real scale tests, and the uplift vertical component ideally due to the sail effect of the wind acting on the tree crown. Elastoplastic strain hardening numerical analyses have been performed (=120N, =-14N; =53mm; =514kPa; =514kPa; =0.3; =150; =3; =20N/mm; =0; =0.75; rotational elastic stiffness has been set to twice the analytical value of). Results are summarized in Figure 6a-b, where the curves and the corresponding loading paths in the plane are shown. The influence of the vertical component is evident and, for the assumed interaction domain, it may induce a substantial difference in the evaluation of the limit moment . In the perspective of the stability assessment of tree against wind gusts, in particular, the particular shape of the interaction domain makes the estimation of limit moment from pulling tests (usually characterized by a positive component, i.e. >0) largely unsafe with respect to uprooting due to wind action.



(a)



(b)

Fig. 6 (a) influence of the vertical load component on curves; (b) loading paths in plane for three different inclination of the applied load.

4 Conclusions

The paper presents the results of a preliminary small-scale testing campaign on 3D printed plastic tree root system. The prototype model has been subjected to vertical tensile and compression tests, and to a horizontal push over test at negligible vertical load and constant moment to horizontal load ratio. The results appear to be consistent with well-known full scale experimental tests available in literature and have been interpreted with the framework of the macroelement theory. A parametric analysis on the main governing parameters has been presented, and, although some additional tests would still be required to fully calibrate the macroement model parameters, a simple calibration strategy has been outlined, focusing the attention on the global of the system (which is commonly studied in arboriculture practice). The influence of the vertical load component on the limit uprooting resistance has also been parametrically investigated. This point is of course strictly related to the assumed shape of the interaction domain at failure, and additional ad hoc experimental tests would still be required with the aim of specifically calibrate an interaction domain for rooting systems. Nevertheless, the numerical results show that disregarding the vertical component (as it is usually assumed by the current interpretation methods of real scale tests) may have an important detrimental influence on the estimation of the ultimate uprooting resistance of the system, thus potentially leading to unsafe estimations.

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