Effect of different wind loading frequencies on tree deflection and uprooting

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Abstract

Tree uprooting is the most common occurrence in hurricanes and storms; however the mechanism is not well known. Numerous attempts have been made to model the damage caused to the trees by the storm. Less is known about the loading condition, which is important for predicting the occurrence of uprooting. In this analysis, numerical models were used to investigate the effect of loading frequency on tree resistance using theoretical soil and root parameters. Results show that tree deflection under wind loading is highly dependent on loading frequency and low-frequency loading is highly probable.

1- Introduction

The growing stock and average age of forests and the constant climate changes observed, with the forecast of stronger windstorms, can also contribute to an increasing risk of wind. When Hurricanes Katrina and Rita bulldozed their way through the Louisiana Coast in 2005, 75% of the trees in New Orleans were stripped down. New satellite imagery has revealed that Hurricanes Katrina and Rita have created the largest single forest disaster recorded in the nation-an entirely unreported ecological disaster that killed or seriously damaged some 320 million trees in Mississippi and Louisiana. Robust pines, oaks, maples and cypresses succumbed to storms, rain and floods. Tree uprooting is the most common event during hurricanes and storms; however the process is not well known. Numerous attempts have been made to model the damage caused by wind to the trees. They led to several predictive models of forest destruction, such as overturning and stem breakage. Experimental studies in which trees are winched until failure and the force required to uproot or trigger stem breakage is measured are useful in providing comprehensive tree-level data (Fraser, 1962; Stokes, 1999; Cucchi et al., 2004; Nicoll et al., 2005; Stokes et al., 2005; Peltola, 2006). These models used empirical relationships to assess the tree's resistance to overturning based on tree-pull tests. They are therefore limited to the conditions of the site on which they were constructed. In addition, the resistance to overturning predicted by these empirical relationships used rough and simplified parametrization.

Vulnerability to uprooting has traditionally been studied at population level, some forest damage is correlated with stand characteristics i.e. tree types, silviculture, soil type, etc (Putz et al., 1983; Ruel, 2000; Cucchi and Bert, 1983; Mayer et al., 2005). However this empiric Wind Throw analysis is incomplete because the characteristics of the root system and other variables influencing tree stability (Khuder et al., 2007) are not always taken into account.

Static analysis of how a tree behaves in the wind is not a reasonable measure and is oversimplification, which can result in incorrect analysis (Mayhead, 1973). The static study suggests that the dynamic sway is not specifically responsible for the windslide and assumes that the trees deflect to the point of failure at constant wind speed. Tree failures at wind speeds were recorded to be less than those expected by static pull tests (Hassinen et al., 1998; Fraser and Gardiner, 1967; Gardiner, 1995; Oliver and Mayhead, 1974), possibly that during hurricanes, the dynamic forces are so different from the test's statically applied forces.

Numerical models were therefore used to investigate the effect of loading mechanisms, soil strength, soil-root interaction and soil form on tree resistance using theoretical soil and root parameters. Less is known about the loading state, which is critical to predict the occurrence of uprooting. The goal of this project is to better understand the process of tree uprooting and to define the impact of loading conditions categorizing as static loading and cyclic loading. This means better understanding of the effect of the loading mechanism on the whole response of the root systems involved in the overturning process. For this purpose, a 2-D FEM model was developed which allowed to simulate various loading mechanisms. Thus the overall strength of the tree anchorage is defined as the product of the contribution of the root system architecture and the static strength of the material. This will allow to investigate the impact of loading and improving risk models that currently do not have any mechanistic relationships to explain tree uprooting.

2-Materials and Methods

2-1-Model details

A tree with a height of 4m and a diameter of 0.4m, modeled for study. A type of root system consisting of horizontal lateral roots has been considered. The root system consisted of two pairs of opposite roots, attached to the vertical tap root at a depth of 0.2 m and 0.6 m from the soil surface, respectively. The length of the tap root and of each shallow side was 1.0 m, and the length of each of the deeper sides was 0.4 m. The two root elements had a diameter of 0.1m. (Figure1 and Table1).

Table1. model Parameters

H	H_{cr}	H_{tr}	D	D_{root}	Depth
4 m	3 m	1 m	0.4 m	0.1 m	1.1m

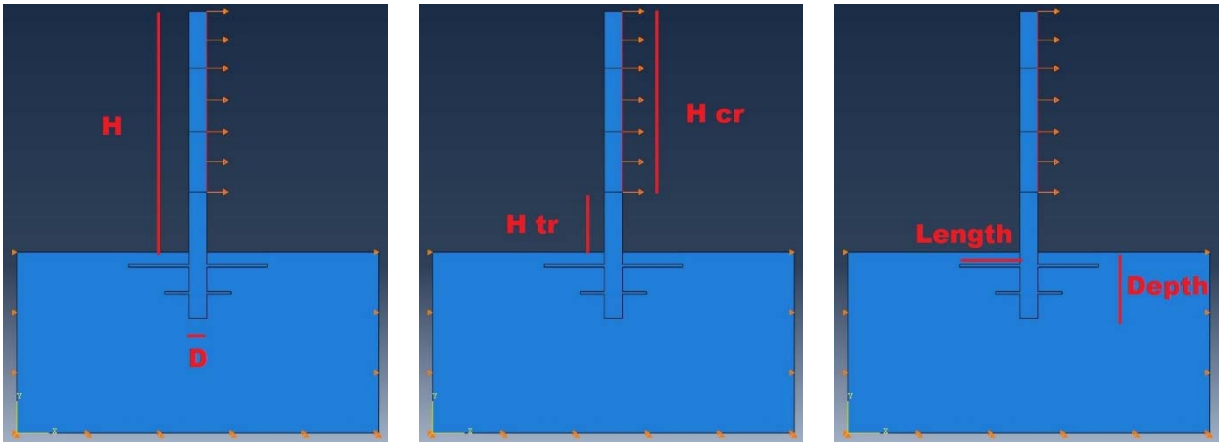

Figure1. Tree and root model parameters

Boundary conditions were applied to the soil domain to ensure the symmetrical displacement of the lateral edges with respect to the vertical Y-plane and the symmetrical displacement of the lower edge of the soil with respect to the horizontal X-plane. Soil and root domains have been meshed using 8-node modified quadratic plane strain squares, CAX8R, available in the ABAQUS element library. Calculation of the Finite Element has taken two steps. The first step allowed the initial geostatic stress to be calculated on the basis of soil and wood mass. The second stage was the horizontal loading of the crown section of the trunk. Horizontal loading applied to the crown portion of the trunk and horizontal deflection shall be measured at trunk height.

2-2-Wind loading

Static analysis treats the wind from a perspective of steady state. Dynamic analysis must take into account changes in the wind caused by gusts as well as the quasi-permanent state variable or the average over a certain period of time. Wind speed can be estimated at any point, but the wind force that is transmitted cannot be measured directly. The wind loading applied to the crown part of tree in both static and cyclic condition. The Frequency of loading selected based on wind pressure spectrum on a wall during a hurricane 0.1 and 1 Hz (Lethford and Norville, 1994).

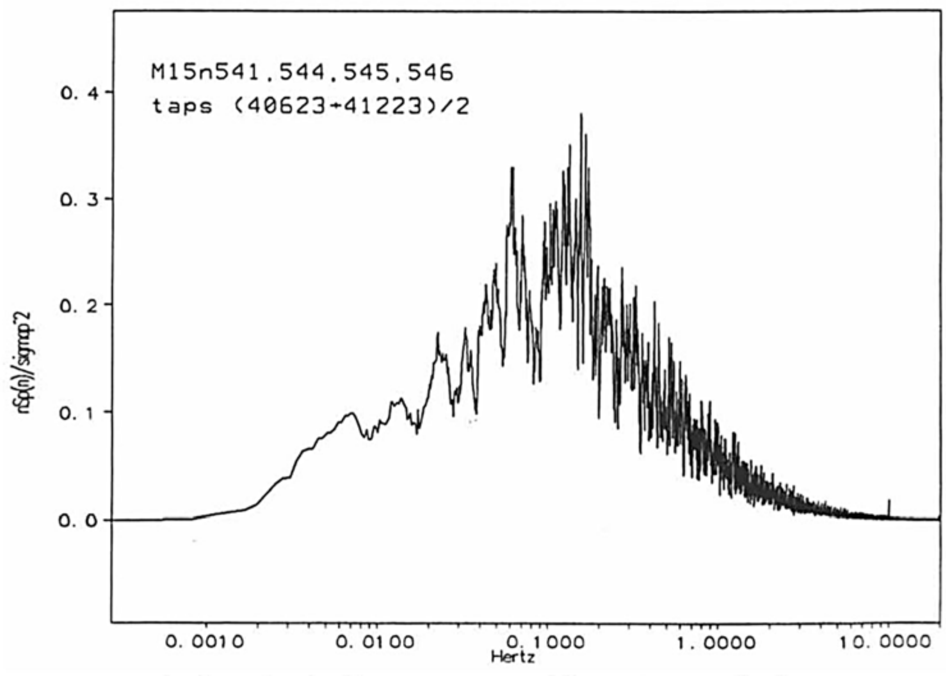

Figure2. Pressure frequency spectrum on a wall during a hurricane

The maximum pressures (P_{max}) of wind are 19 and 38 psf which is corresponding to hurricanes with category1 and 3 (Coder, 2018) (Figure3).

storm category	wind speed mph	mid-point wind pressure* lbs/ft²	tree impacts
1	74-95	19	branch & tree failures
2	96-110	28	major tree failures
3	111-130	38	large tree failures – leaves gone
4	131-155	54	massive tree blow-downs
5	> 155	> 63	most trees down

Figure3. Saffir-Simpson hurricane scale with tree impacts (Coder, 2018)

In each test, the pressure increases linearly until reaching to the maximum value of P_{max} and after that decreases to reach the $-P_{max}$. The time of test selected 60s and by selecting 0.1Hz and 1Hz, the total cycles would be 6 and 60 respectively (Figure4 and Table2)

Table2 : Loading Parameters

Wind pressure	Loading area	Frequency	Time of loading
38 psf (3640 kPa)	6 m^2	0.1 and 1 Hz	60 s

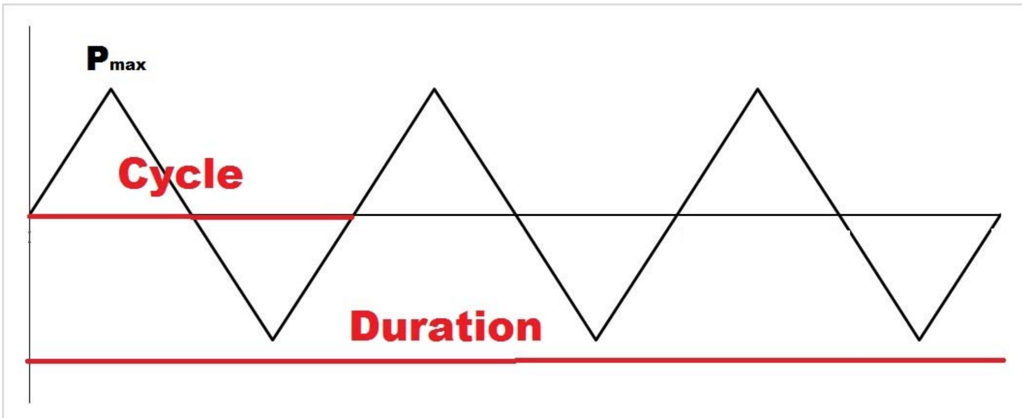

Figure4. Loading cycles

2-3- Soil and Wood characteristics

In this analysis, two contrasting theoretical soils S1 and S2 (Table 1) were considered to be indicative of saturated soft clay and low-cohesion loamy sand (total lack of cohesion may lead to difficulties in numerical convergence). Both soils have been modeled as an elastic, fully plastic substance, i.e. without hardening consideration (Dupuy et al., 2005a, b). The yield criterion that defines the limit of soil failure was established by the Mohr-Coulomb model, which assumes that the maximum shear stress (τ) regulates failure and that τ depends on normal compression stress σ, which is conventionally negative. This Mohr–Coulomb linear criterion was expressed as $\tau = c + \sigma * \tan \emptyset$, where c is soil cohesion and $\emptyset$ is soil internal angle of friction. The elastic part of the soil constitutive law was assumed to be linear isotropic and governed by the Young's modulus E_{soil} and Poisson's ratio μ_{soil}. Values of soil mechanical parameters that were used in the simulations are given in Table3.

Table3. Soil Parameters

	Constitutive model	Elastic Modulus	Poisson ratio	$\emptyset$	C	ψ
S1	Mohr-coulomb	20 MPa	0.4	25	1.5 kPa	0
S2	Mohr-coulomb	20 MPa	0.4	0	20 kPa	0

Wood material was considered to be elastic linear and characterized by a Young's Modulus E of 2.0 GPa and a Poisson's coefficient μ_{wood}=0.3. The density of wood was 1000 kg/m^3 (Dupuy et al., 2005a) and the soil density is 1500 kg/m^3 respectively (Table4).

Table4. Wood Parameters

Constitutive model	Elastic Modulus	Poisson ratio	Yield stress
Elasto plastic	2 GPa	0.3	15 MPa

3-Results

In this study, a total of ten 2D FEM models of trees under wind loading modeled and tested (Table5). Two models with static loading tested for comparison with dynamic cases.

Table5. Tests program

Number of test	Loading condition	Frequency	P_{max}	Type of soil
1	Static	-	38 psf (3640 kPa)	S1
2	Static	-	38 psf (3640 kPa)	S2
3	Dynamic	1	38 psf (3640 kPa)	S1
4	Dynamic	1	38 psf (3640 kPa)	S2
5	Dynamic	1	19 psf (1820 kPa)	S1
6	Dynamic	1	19 psf (1820 kPa)	S2
7	Dynamic	0.1	38 psf (3640 kPa)	S1
8	Dynamic	0.1	38 psf (3640 kPa)	S2
9	Dynamic	0.1	19 psf (1820 kPa)	S1
10	Dynamic	0.1	19 psf (1820 kPa)	S2

The results of the finite element simulations show that tree deflections and responses to hurricane winds are very sensitive to loading conditions. The results of the models show that the response of the tree to the cyclic loading is highly dependent on the loading frequency. Both models with a loading frequency of 0.1Hz and 1Hz achieve failure. It means that the deflection of the point at the top of the tree reaches 2m and increases exponentially afterward (Figure5).

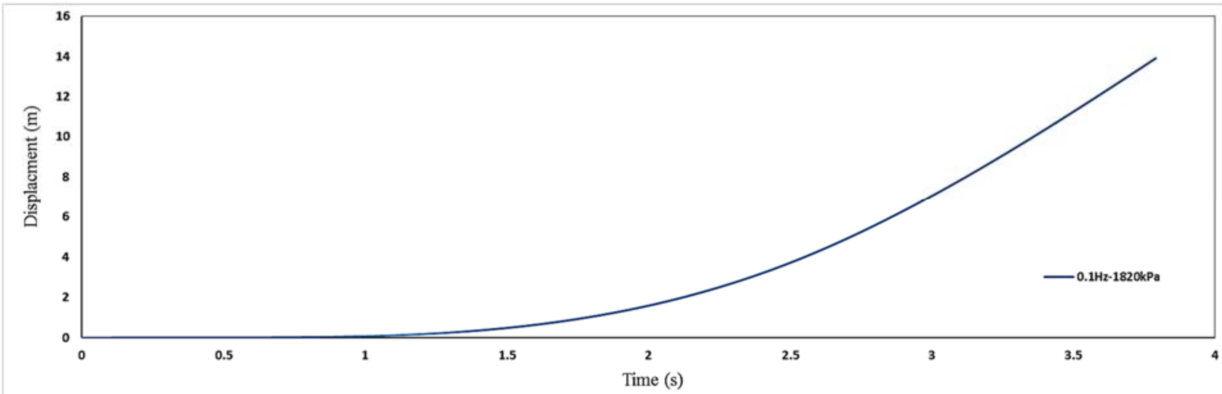

Figure5. Time history of deflection for tree under 0.1 Hz loading on Soil type 2

The development of shearing zones in the soil and deflection without bending in the trunk indicates that uprooting occures (Figure6).

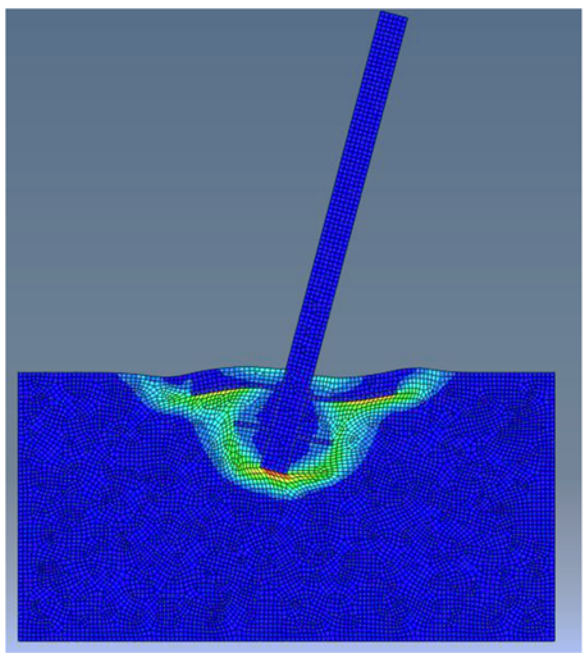

Figure6. Plastic shear strains in soil results in uprooting

For models with a loading frequency of 1Hz, soil type 2 trees display a maximum deflection of around 0.08m and 0.06m at maximum pressures of 3640 and 1820 kPa, respectively (Figure7). Full deflection is the product of dynamic deflection and there is no residual deflection left after loading. The static loading with 3640kPa pressure, results in convergence error after reaching the 0.02m deflection for soil type 2.

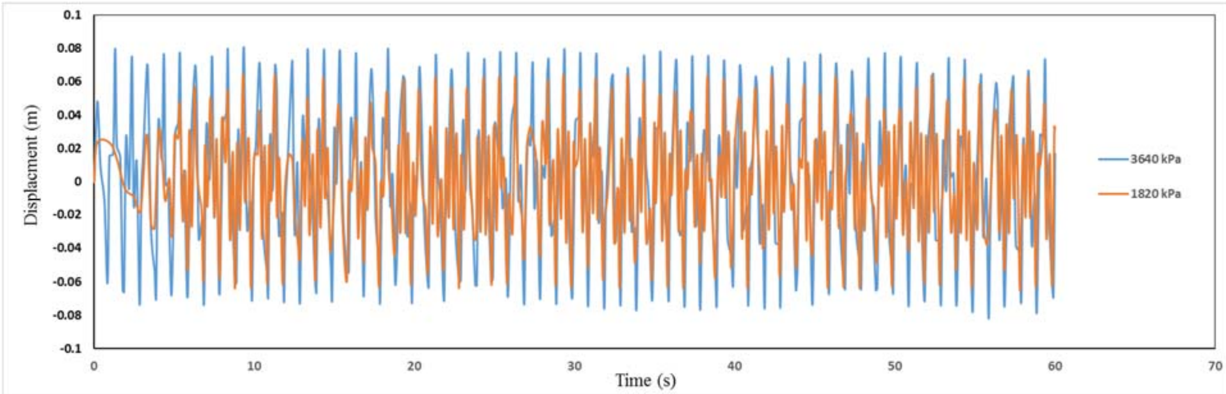

Figure7. Time history of deflection for tree under 1Hz loading on Soil type 2

Models of soil type 1 achieve high deflections near failure even with a loading frequency of 1Hz. The results show that the dynamic deflection of trees on soil type 1 is approximately 0.75m and 0.4m for maximum pressures of 3640 and 1820 kPa, respectively, and is almost constant for each pressure during loading. However, after a few cycles, residual deflection decreases and remains constant (Figure8). Static loading at 3640kPa results in0.043m deflection for the soil type 1, which is very different from the dynamic analysis results.

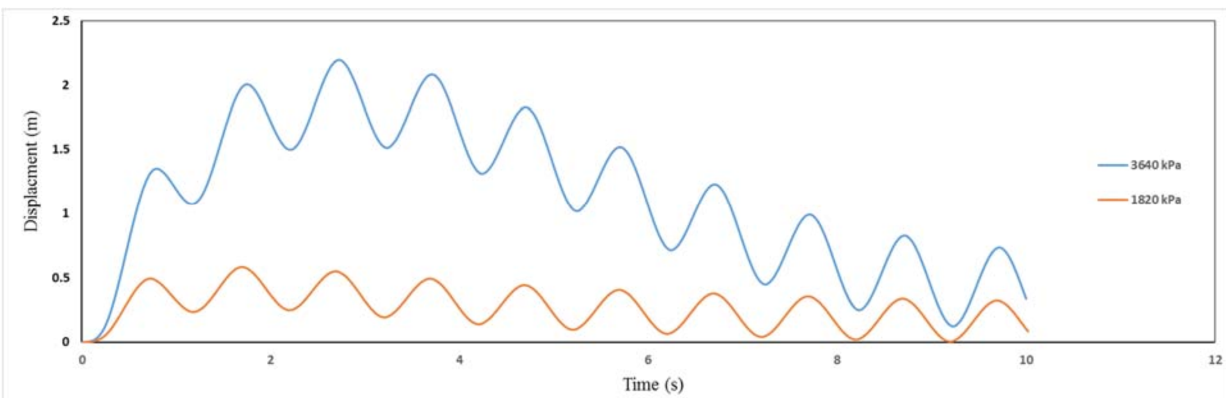

Figure8. Time history of deflection for tree under 1Hz loading on Soil type 1

4-Conclusion

The results from the tests show that the response of trees to cyclic loading is highly dependent on loading frequency. As we now for structures, there is a phenomenon which is called intensification. Intensification happens when the frequency of dynamic loading is very close to the natural frequency of structure resulting in amplified deflection and failure in structures. For tree uprooting, the same phenomenon occurs when the frequency of loading is similar to the frequency of wind. Hurricane data indicate that there is no fixed frequency of wind loading during the hurricane, and the frequency range can vary from 0.01Hz to 10Hz. In addition, the natural frequency of the trees is very different and depends on the hardness of the tree and its root and soil properties. Thus the occurrence of tree uprooting may be treated as a loading of earthquakes on structures. However there are minor variations, such as building deflection limitations and tree root-soil interactions. As a consequence, a thorough study, including in situ tests and numerical studies, is required to obtain a strong conclusion for loading effects on tree uprooting. The findings of the present study show:

1- There is a big difference between the results from static loading and dynamic loading.

2- Low wind loading frequency (0.1 Hz) even with low pressures causes failure and uprooting in tree.

3- Uprooting resistance is higher in soil type2 (S2) which has greater cohesion.

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