Key words:
intelligent information system, tornado, weather modeling, Rankine vortex, HWIND tree damage model

Radosław CHMIELARZ and Jarosław WĄS

AGH - University of Science and Technology, Krakow

SYSTEM FOR SIMULATING TORNADO DAMAGES IN FORESTS

The aim of this paper is to provide an overview of an intelligent information system dealing with simulation of tornado damages inflicted in forests. The system is potentially useful for forests managers in delivering information about optimization of newly grown tree stands against tornado damages in regions endangered with severe wind gusts.

The system consists of a combined Rankine vortex used for tornado simulation and of HWIND tree damage model used for assessing tornado impact on forests. The Rankine vortex equations have been expanded to three dimensions using real tornadoes data. The HWIND model has been modified to be used for sudden wind blows conflicted by tornadoes in contrast to constant wind speeds for which it was designed. Never before had all the equations for Rankine vortex and HWIND tree damage model been gathered in one paper. The simulation is visualized by the system and results in a pattern of downed trees from which suitable conclusions for forest managers are made.

The authors believe that the work is important as Europe is struck by tornadoes which conflict damages worth billions of euros every year, mostly in unpopulated areas such as forest. Moreover the scientific literature on this topic in Europe is sparse.

1. INTRODUCTION

It may seem that tornadoes are not frequent events in Poland, but only in 2010 European Severe Weather Database [2] has collected 83 reports of severe wind gusts - sudden winds blowing with speeds over 25km/h and 18 tornadoes. The meaning of tornado's damages is also notable as in 2008 windstorm Emma, crossing Central Europe, conflicted damages estimated by over 1 billion euros.

The topic of tornado modeling is also not widely described in European literature and up to this date there was no article putting all the equations for HWIND tree damage model in one place. HWIND model plays a central role in estimating effects of wind gusts on trees in forests.

2. SYSTEM OVERVIEW

The system consist of two models: vortex and tree damage. For the vortex model Rankine's method was chosen. Its purpose is to give a wind speed value for a given point in space in the area struck by a tornado. The second model was implemented by HWIND tree damage model which task is to provide maximum bending force for a particular tree which is necessary for that tree to be either broken or uprooted by wind. The result of simulation based on those two combined sub-models is a downed tree pattern. From the downed tree pattern one can infer the impact of changes in model's attributes on trees in the forest and in consequence deduct how to protect forests from tornado effects.

A class diagram for the system is given in figure 1. The classes corresponds directly to models used. **GUI** class is the interface between user and the rest of the system. **Simulation** class is responsible for running a simulation in loop until the center of the vortex is out of the simulated forest area. The **Simulation** class uses **AbstractVortexModel** which is a parent class for Rankine which purpose is to provide calculations from Rankine vortex model. **ForestModel** class is responsible for gathering data about trees in the forest by using calculations for single tree take from **HWIND** class which is a child class of **AbstractTreeModel** and uses **HWINDData** class for particular tree species used in the system.

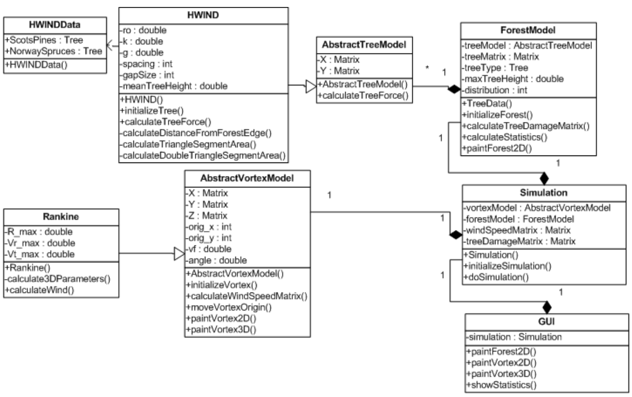

Fig. 1. System's class diagram. *Source: original work.*

A sequence diagram is given in figure 2. First the user has to provide parameters of the tornado, which include vortex origin coordinates, speed and direction of the move of tornado, maximum vortex radius and maximum wind speeds in the tornado. Next the user has to choose what tree species are growing in the forest. In the forest only one type of trees can be simulated due to HWIND tree damage model's limitation which impose a forest has to be homogenous. The user is also asked to estimate the average age of trees in the forest which is represented by maximum height of a tree. Data on trees' species parameters are stored in **HWINDData** class.

The simulation is done on a grid. On each intersection grows a tree and by manipulating the distance between them and the area of simulated location one can manage forest density.

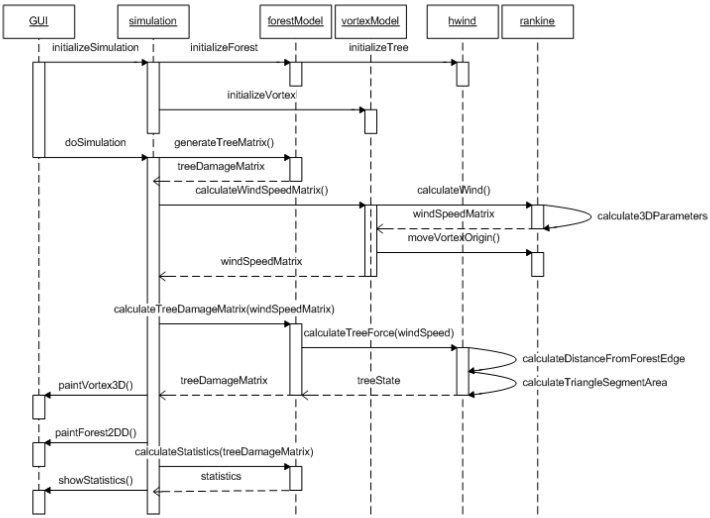

Fig. 2. System's sequence diagram. *Source: original work.*

When the start button in the application is pressed the sequence is started. The grid is initialized by **initializeSimulation()**, forest parameters are set in **initializeForest()**, tree specie is set in **initializeTree()** and finally vortex attributes are set by **initializeVortex()**. When the simulation is started in **doSimulation()** trees attributes are drawn from random number generator in **generateTreeMatrix()** and a blank ***treeDamageMatrix*** is put in ***simulation*** object. Next wind speeds on the intersections of the grid are calculated in **calculateWindSpeedMatrix()**, which in turn uses **calculateWind()** method which calculates wind speeds of a tornado vortex in three dimensions using **calculate3DParameters()**. The new origin point of the vortex center is calculated and moved accordingly to its transition speed vector in **moveVortexOrigin()**. The result of this step is a ***windSpeedMatrix***. The speeds from ***windSpeedMatrix*** are used to check if the wind has inflicted any damage in the forest in **calculateTreeDamageMatrix()**. This is done by calling **calculateTreeForce()** on each tree in the forest which calculates equations from HWIND tree damage model and gives an answer on the

treeState which can be either broken, uprooted or standing still. The ***treeDamageMatrix*** is returned to ***simulation*** object which uses ***windSpeedMatrix*** and ***treeDamageMatrix*** to display them to the user by calling **paintVortex3D()** and **paintForest2D()** methods of ***gui*** object. The last step is to gather ***statistics*** of downed trees in the forest and display them to the user. If the origin of the vortex is still in the area of the grid the next step of simulation is computed. If not the simulation ends and the user is presented with complete downed tree pattern.

3. RANKINE VORTEX MODEL

Rankine vortex is a steady-state vortex model developed in the middle of XIX century [4a]. It consists of two regions. In the inner region wind speed is rising linearly with the rise of distance from the center of the vortex. Speeds in the outer region are behaving in the opposite way, where they lower with the rise of distance from the vortex center. The border between regions is defined by radius **R**. The situation can be seen in figure 3.

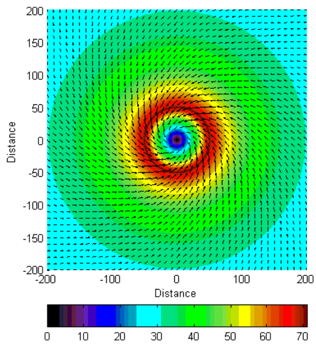

Fig. 3. Rankine vortex 2D visualization. *Source: original work.*

Equations for the vortex are best presented in polar coordination system. Tangential velocity V_φ is calculated from the equation (1) and the radial velocity V_r is calculated according to equation (2).

$$V_\varphi = \begin{cases} V_{\varphi,max}\left(\frac{r}{R_{max}}\right), & r \leq R_{max}, \\ V_{\varphi,max}\left(\frac{R_{max}}{r}\right), & r > R_{max}, \end{cases} \tag{1}$$

$$V_r = \begin{cases} V_{r,max}\left(\frac{r}{R_{max}}\right)^{0.6}, \; r \leq \; R_{max}, \\ V_{r,max}\left(\frac{R_{max}}{r}\right)^{0.6}, \; r > R_{max}. \end{cases} \tag{2}$$

In the equations r is the distance of each point in the grid from the vortex center and R_{max} is the size of inner vortex region. Exponentiation of equation (2) was approximated to 0.6 in [1] by measuring radial velocities of tornadoes by mobile Doppler radar.

Total wind speed of a tornado in each point of the grid is a superposition of tangential and radial velocity vectors plus the forward velocity of vortex center which emulates a moving tornado.

Rankine model is two dimensional but the authors of this publication have expanded it to third plane. It has been done by making the maximum radius R_{max} and tornado center coordinates (x_0, y_0) dependent on the height z. There are many tornado shapes but in this work V-shaped tornadoes were chosen.

Authors have gathered pictures of real V-shaped fully connected to the ground tornadoes. Then by measuring landscape objects on the pictures a scale for each picture was estimated. Next step was to select tornado shapes from the background, convert pictures to black and white and with the help of MATLAB Image Processing Toolbox estimate radius and center position on each height z. Finally all data points where averaged and approximated to functions. Because pictures showed vortexes only from one angle it was decided that the resulting 3D model will computed by using the same equation for both x and y-plane. Estimated functions for radius R_z is shown in equation (3) and the center (x_z, y_z) is shown in equation (4).

$$R_z = (-8.5637 \cdot 10^{-8}z^3 + 0.00018695z^2 + 0.0078765z + 0.94933)R_0 \tag{3}$$

$$x_z = x_0 + (1.3142 \cdot 10^{-7}z^4 - 3.864 \cdot 10^{-5}z^3 + 0.0048048z^2 - 0.10169z - 0.46675)\frac{R_0}{5}$$
$$y_z = y_0 + (1.3142 \cdot 10^{-7}z^4 - 3.864 \cdot 10^{-5}z^3 + 0.0048048z^2 - 0.10169z - 0.46675)\frac{R_0}{5} \tag{4}$$

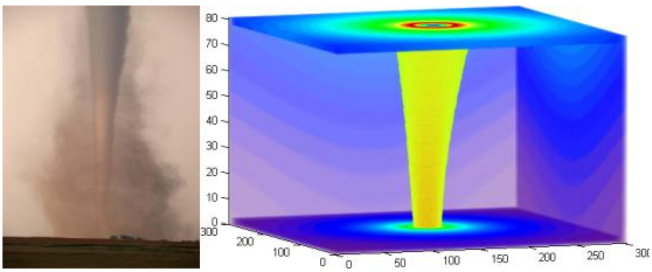

Fig. 4. Comparison between real tornado shape and Rankine vortex 3D visualization. *Source of the tornado image: [5]*

Figure 4 compares real tornado (not present in the learning set) with the visualization.

4. HWIND TREE DAMAGE MODEL

HWIND model was designed in University of Joensuu in Finland [6a]. Its purpose was to simulate trees resistance to constant winds blowing within 10 minutes range 10 meters from the ground on podzolic soil.

Forces acting on the trees are shown in figure 5. First the tree is divided on 1 meter segments and forces are computed for each segment. In the end the segment's forces are summed and the result is the total force acting on a tree.

Total wind-induced forces F_w are written in equation (5). Parameter z is the height (segment number) above the ground in meters, C_d is a dimensionless drag coefficient given in table 1, ρ is the air density, v_h is the wind speed on given height and $A(z)$ is the projected area of each tree segment giving resistance to the wind.

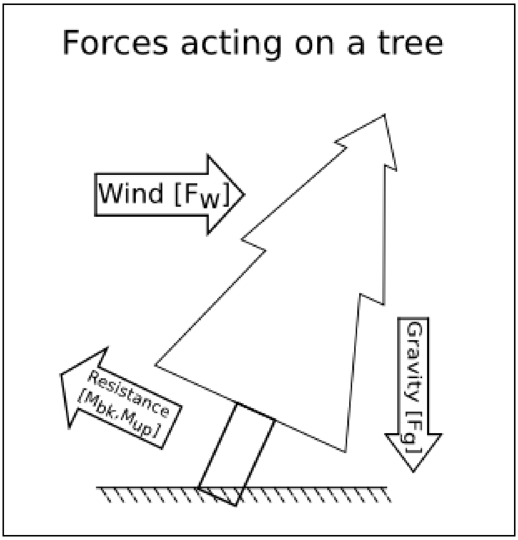

Fig. 5. Forces having impact on a tree. *Source: original work.*

Two type of tree species are modeled: Scots Pine and Norway Spruce, which are the most popular tree types in Polish forests [9]. Each of them has a distinct crown shape which was approximated by an equilateral triangle in case of Scots Pine and by two equilaterals triangles connected to each other with their bases in case of Norway Spruce. The canopy of a tree was approximated by a rectangle. In consequence segment projected area $A(z)$ is a 1 meter fragment of either the rectangle representing tree canopy or a slice to triangle representing tree crown depending on the height above the ground.

$$F_w(z) = \frac{1}{2} C_d \rho v_h^2 A(z) \tag{5}$$

As the wind blows on the tree the area of the crown is reduced. If the wind blows with speeds below or equal to $11\frac{m}{s}$ then the area is reduced by 20%. If the wind speed is over $20\frac{m}{s}$ then the area is reduced by 60 %. And if the wind velocity is in between the shrinking factor S_t is computed from equation (6).

$$S_t(z) = \frac{10}{v(z)} - 0.1 \tag{6}$$

Table 1. Data for HWIND tree damage model. *Source: [7]*

Parameter	Scots Pine	Norway Spruce
Modulus of rupture (MOR)[MPa]	39.1	30.6
Modulus of elasticity (MOE) [MPa]	7000	6300
Air density (ρ) $\left[\frac{kg}{m^3}\right]$	1.226	1.226
Drag coefficient (C_d)	0.29	0.35
Soil mass to tree mass ratio (f_{RW})	0.3	0.2
Crown approximation shape	Triangle	Double triangle

After the tree is bend by the wind gravitational force F_g in equation (7) starts acting on each segment. Here m_c is the mass of each tree segment.

$$F_g(z) = m_c g \tag{7}$$

Finally total bending moment B_{max} for each segment $z$is the sum of wind-induced force F_w multiplied by the height z and gravitational force F_g multiplied by the horizontal displacement from upright of the segment. The sum is further multiplied by gust factor f_{gust} and gap factor f_{gap} described later in the paper.

$$B_{max}(z) = f_{gust} f_{gap} \left[F_w(z)\Delta z + F_g(z)x(z)\right] \tag{8}$$

Horizontal displacement of a segment $x(z)$ is presented in equation (9). Here a means the height from the ground to the middle of the crown, h - total height of the tree, $l(z)$ distance from the tree top to the height z, modulus of elasticity MOE given in table 1, I is the area moment of inertia of the tree stem m^4 which equals to $I = \frac{\pi d_{bh}^4}{64}$, where d_{bh} mean the tree diameter on the breast height (1.3 m). Equation is divided in two parts. In the first part the segment z being calculated is below the height of the middle of the crown and in the other part it is above.

$$x(z) = \begin{cases} \dfrac{F_w a^2 h\left(3-\frac{a}{h}-\frac{3l(z)}{h}\right)}{6\cdot MOE\cdot I}, & z \leq a, \\ \dfrac{F_w a^3\left(2-\frac{3(l(z)-b)}{a}+\frac{(l(z)-b)^3}{a^3}\right)}{6\cdot MOE\cdot I}, & z > a. \end{cases} \tag{9}$$

Each segment maximum bending moments $B_{max}(z)$ are summed together resulting in the total bending moment B_{max} for a tree.

In a research conducted in 2005 Gardnier and Stacey [8] showed that trees behave differently under wind pressure if they grow in different distances from the forest edge and apart from each other. Suitable equations are shown in (10) and (11).

$$Gust_{mean} = \left(0.68\frac{s}{h} - 0.0385\right) + \left(-0.68\frac{s}{h} + 0.4875\right)\left(1.7239\frac{s}{h} + 0.0316\right)^{\frac{x}{h}}$$

$$Gust_{max} = \left(2.7193\frac{s}{h} - 0.061\right) + \left(-1.273\frac{s}{h} + 9.9701\right)\left(1.1127\frac{s}{h} + 0.0311\right)^{\frac{x}{h}} \tag{10}$$

$$f_{gust} = \frac{Gust_{max}}{Gust_{mean}}$$

$$Gap_{mean} = \frac{0.001+0.001p^{0.562}}{0.00465}$$

$$Gap_{max} = \frac{0.0072+0.0064p^{0.3467}}{0.0214} \tag{11}$$

$$f_{gap} = \frac{Gap_{max}}{Gap_{mean}}$$

Furthermore in the tunnel experiment it was noted that the first row of trees in an artificially grown forest has larger resisting force than those trees growing in the middle of the forest. It is suspected that this phenomena is connected to wood density in the outer trees and the airflow inside the forest.

The above equations were connected to the forces applied on a tree. In equations (12) and (13) resistive forces are shown.

$$M_{bk} = \frac{\pi}{32} MOR d_{bh}^3 \tag{12}$$

Stem breakage resisting force M_{bk} is a product of outer fiber layer resistance on the breast height (1.3 m). The tree is assumed to bend to a point of no return which results in breakage of the stem.

$$M_{up} = \frac{gR_{mass}R_{depth}}{f_{RW}} \tag{13}$$

Resistance to a tree uproot M_{up} is a multiplication of gravitational force g, root's mass R_{mass}, root's depth R_{depth} and a ratio of soil mass around the roots to the whole tree mass f_{RW}. If the forced is exceeded the tree is assumed to be uprooted.

Lastly HWIND model assumes that the wind is blowing constantly with the same velocity for at least 10 minutes and in consequence bends the tree to a point of no return. However as tornadoes are a sudden and violent phenomena it was shown by other researchers [3] that its wind blows velocities v_{sudden} correspond to mean wind velocities v_{mean}. The reliance was approximated by authors to equation (14).

$$v_{mean} = -0.0032158 v_{sudden}^2 + 0.54722 v_{sudden} - 0.1285 \tag{14}$$

5. RESULTS

Downed tree pattern from system's simulation has been compared to an image of a real forest after a tornado had passed through it. As it can be seen in figure 6 the simulation has captured main characteristics of a real downed tree pattern. The damaged area of the forest is narrow as in the simulation and some trees had been broken while others uprooted. Moreover downed trees are aligning in semicircles as in the simulation.

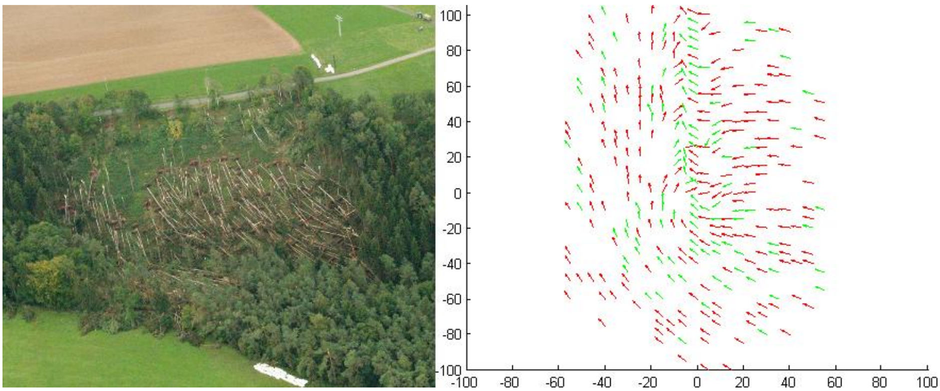

Fig. 6. Comparison between image of a forest after a tornado has passed through it and downed tree pattern from system's simulation. Area of damage is approximately 120 m wide; forest consist of Scots Pine from 12 to 16 m height with distance of about 5 m between trees; tornado is estimated as T6 (73-83m/s) with 8 m in diameter at the ground. *Source of the image: [10]*

Downed tree patterns from simulations with different values of each simulation parameter have also been compared to each other and conclusions for forest managers have been drawn:

- Tree height – as expected the force needed to break or uproot a tree grows with the height and diameter of a tree. However the force needed to uproot a tree for thin and small trees is bigger than the force needed to break them, this trend is inverted when it comes to big and thick trees.

This dependence can be explained by relatively small root mass growth with tree age and over proportional growth of tree's stem and crown.

- Tree species – Scots pine require greater wind speeds than Norway Spruce in order to be broken or uprooted, therefore forest manager can consider planting trees species which are more resistant to the winds.
- Distance between trees – the lower the distance between trees the greater force is needed to break or uproot them. Therefore densely populated forests are more resistant to tornadoes, however the system in current shape doesn't take into account effects of broken trees falling on each other.
- Upwind gap – the bigger the upwind gap in front of forest edge the more resistant are the trees to tornado damage. The possible cause of this effect may be that winds in narrow spaces are blowing faster than in wide spaces. Therefore forest managers may consider leaving a gap in front of forests in order to strengthen them against sudden winds.
- Mean tree height – the bigger mean height of trees in the forest the more resistant the trees are to tornado damages. The cause of this is that bigger trees are protecting the smaller ones and therefore collectively less trees are downed in the forest. The conclusion for forest managers is that newly grown trees could be planted in between areas with older trees.
- Distance from forest edge – the force needed to down a tree rises with the rise of the distance from the forest edge up to a point and then it starts to fall as the distance is bigger. The cause is believed to be connected with wind flow in narrow spaces [8a]. And the conclusion for forest managers is that newly grown trees should be grown in front of an area closed by older trees.

6. CONCLUSIONS AND FURTHER WORK

A system for simulating tornado damage in forests have been shown. The authors have presented all the equations for HWIND tree damage and Rankine vortex models. Rankine vortex has been expanded with equations related to its shape in third dimension based on real tornado data. The HWIND tree damage model has been expanded with equation which translates constant speed of wind blowing in one direction for a period of time to the speeds of sudden winds present in tornadoes. The model, although simple in construction, has met expectations in analysis of tornado characteristics.

From simulation results conclusions for forest managers have been drawn and presented in chapter 5.

In further works the authors will try to overcome current model limitations by introducing second hand effects such as the impact falling trees have on their neighbors. The future work could also benefit from studying airflow in narrow spaces and the difference of wind speeds on different heights above the ground.

REFERENCES

[1] BLUESTEIN H., *Mobile Doppler radar observations of tornadoes*, Preprints. 4^{th} European Conference on Severe Storms, 2007.
[2] *European Severe Weather Database,* http://www.essl.org/ESWD/.
[3] GARDINER B., PELTOLA H., KELLOMAKI S., *Comparison of two models for predicting the critical wind speeds required to damage coniferous trees*, 1999.
[4] GIAIOTTI D.B.,STEL F., *The rankine vortex model*, Visco, Italy, University of Trieste, 2006.
[5] HUMPAGE M., http://www.markhumpage.com/Mother-Nature/Sever-Weather/, 2008.
[6] PELTOLA H., KELLOMAKI S., *A mechanistic model for calculating windthrow and stem breakage at stand edge*, Silva Fennica, 27:99–111, 1993.
[7] PELTOLA H., KELLOMAKI S., VAISANEN H., IKONEN V., *A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of scots pine, norway spruce and birch*, 1999.
[8] PELTOLA H., *Mechanical stability of trees under static load*, 2006.
[9] *Polskie Lasy Państwowe*, http://www.lasy.gov.pl/o_lasach/polskie_lasy, 2010.
[10] STREMKE D., *LaNaServ*, http://www.lanaserv.de, 2006.