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Wind Fragility for Urban Street Tree in Korea

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강풍 발생 시 국내 가로수의 취약성 분석

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Abstract

In this paper, the analytical method to derive wind fragility for urban street tree in Korea was shown. Monte Carlo Simulation method was used to determine the probability of failure for urban street tree. This probability result was used to determine wind fragility parameters for four types of tree based on the study of street tree species in urban area in Daegu, Korea. Wind fragility for street tree was presented in terms of median capacity and standard deviation of the natural logarithm of the capacity. Results showed that the dominant factor affecting the probability of failure of tree under wind load was their diameter. Moreover, amongst the four types of tree chosen, the tree with height 7m and diameter 35cm had the lowest probability of failure under wind loading, whereas the tree with height 8m and diameter 30cm could resist the least wind loading. The median failure wind speed for urban street tree with height 7m were 43.8m/s and 50.6m/s for diameter 30cm and 35cm, respectively. Also, for tree with height 8m, their median failure wind speeds were 38.7m/s and 45.4m/s for tree with diameter 30cm and 35cm, respectively.

Key words : Monte Carlo Simulation, tree critical breaking moment, urban street tree, wind fragility

요 약

이 논문에서는 한국의 가로수에 대한 바람 취약성을 유도하는 분석 방법을 보여준다. 몬테 카를로 시뮬레이션 방법은 도시 가로수의 파괴 확률을 결정하는 데 사용되었다. 이 확률 결과는 대구 지역의 가로수를 기반으로 4 가지 유형에 대한 바람 취약성 매개 변수를 결정하는 데 사용되었으며, 이로 인해 풍하중에서 가로수 손상 확률에 영향을 미치는 주요 요인이 직경이라는 것을 나타낸다. 또한, 선택된 4 가지 유형 중에서 높이 7m, 직경 35cm의 가로수는 손상률이 제일 낮은 반면, 높이 8m, 직경 30cm의 가로수는 가장 낮은 풍하중에서 저항하였다. 높이 7m의 가로수의 평균 손상 풍속은 직경 30cm 및 35cm에 대해 각각 43.8m/s 및 50.6m/s로 나타났으며, 높이 8m의 가로수의 평균 손상 풍속은 직경 30cm 및 35cm에 대하여 각각 38.7m/s 및 45.4m/s로 나타났다.

핵심용어 : 몬테카를로 시뮬레이션, 나무 파괴 거동, 가로수, 바람 취약성

1. Introduction

Structural damages caused by natural disaster phenomena are reported to be steadily increasing due to recent abnormal climate phenomena and the increasing frequency of natural disasters globally. Lee et al. (2017) estimated the maximum annual damage costs from natural disasters through 2060 in Korea will be US$20.9 billion, which equal to 1.03% of future Korean gross domestic product (GDP). Moreover, the damages due to typhoon not only caused devastating loss on the economy, but also threatened the safety of human life. Therefore, the risk assessment for structure subjected to strong wind had gained many attentions. Probabilistic risk assessment (PRA) has risen as an increasingly popular analysis tool. PRA is a comprehensive and systematic procedure to estimate risks.

Wind fragility is an essential part of the development of PRA for strong wind disaster management framework, they present the probability of failure of structure or structural element in term of wind intensity. Many researches were focused on the development of wind fragility for structure or structural elements such as wood frame structure (Ellingwood and Rosowsky, 2004; Lee and Rosowsky,

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2006), industrial building (Ham et al., 2009; Lee et al., 2013), roof sheathing (Lee and Rosowsky, 2005), protruding advertisement sign (Sim et al., 2018), etc. This trend leads to inadequate information for management and maintenance purposes of natural asset such as urban tree. In fact, street trees have played a significant role in the urban landscape. They provide considerable benefits extending from physiological and economic benefits to the improvement of urban climate and mitigation of air pollution. Many studies have shown the urban forest can provide physical environment and biological benefits (Sagi, 2016). Moreover, they have significant environmental values such as purification of air and water (Neville, 1996; Nowak, 1994), reducing of wind and noise disturbance (Aylor, 1972), stabilization of microclimate (McPherson, 1994), natural areas deliver social and psychological benefits (Nowak, 2002), which are of crucial significance for the livelihood of modern cities and the well-being of urban residents (Chiesura, 2004). Similarly, Korea has also focused on the urban greening to improve the well-being and living standard of urban citizen. However, the urban greening has mainly focused on the beautification which resulted in the lack of risk analysis for this importance city landscape component.

The stability of tree subjected to wind loading has garnered many growing concerns in many parts around the world (Sagi, 2016). Recent typhoon events showed the disruption and damage caused by failure of urban tree (Fig. 1), such as fallen trees on motor way, walkway, power lines, vehicles, private property, etc. Moreover, the most prominent problem for urban area is land scarcity which forces the trees to grow closer to urban structures. This resulted in the increasing risk to structural damage and peoples' safety due to failure of tree under extreme wind events. The damage and loss of life have led to an increased interest in research related to tree stability. Therefore, to contribute to this research interest, the performance of common street tree under strong wind was presented in statistical viewpoint. In this study, wind fragility development method for typical street tree was presented to demonstrate the notion of using probabilistic approach to assess the safety of urban street tree. This notion no longer thinks of each variable as a single value or number. Instead, each variable is viewed as a probability distribution.

2. Stability of tree under wind loading

2.1 Tree-pulling field test

The key factors that affect the failure of a healthy tree and root system were their diameter at breast height, height, crown frontal area, stem volume, stem breakage strength, root plate architecture, depth, diameter, weight, and the strength of soil and roots (Sagi, 2016). Im et al. (2011) performed field study of tree-pulling test to investigate the critical breaking moment. This critical resistance force could be used to measure the level of resistance that tree could resist the external force. In their study, the relevant factors

Fig. 1. Disruption and damage due to fallen trees during typhoon (image from Korean local news website)

for determining the critical breaking moment for tree were external characteristic of tree, tree height and tree diameter at breast height. In fact, they tested the resistance limit of 100 shrubs and tall trees. Consequently, they determined that the relationship between critical moment and diameter at breast height showed the highest correlation coefficient. They proposed a new coefficient α for optimal regression equation of tree's critical breaking moment in Korea should be 6.0.

$$M_c = \alpha D^2 \quad (1)$$

In which M_c is the critical breaking moment in kgf.m, D is the tree diameter at height 1.2m in cm, and α determined by the pull-test which proposed to be 6.0.

2.2 Parameters of common tree in Korea

Yoon et al. (2013) studied and presented the general external characteristics of five tree species in Daegu, Korea. Moreover, they developed simple linear regression between crown area (C_A) and diameter at breast height (D). These linear regression equations could be used to estimate the general external characteristics of common urban street tree in Korea. These characteristics were used to determine wind load parameters and wind loading area on the tree.

In this study a simple model was used to present each tree. In Fig. 2, a tree with a cylindrical stem with diameter D at height 1.2m, a cylindrical crown with length C_L and diameter C_D, and tree height H. Additionally, Table 1 shows the average crown area of urban street tree in Korea, estimated to be around 20m^2 and the diameter at 1.2m was between 30cm ~ 35cm. In this paper, two cases of tree height were chosen which were 7m and 8m which resulted in a total of four cases of tree characteristics combination. Each case was used in the determination of wind fragility for three different wind exposure categories. Wind exposure category reflects the characteristics of ground surface irregularities for which the tree located (ASCE-7, 2010), they consisted of:

- Exposure B: urban and suburban areas or other terrain with numerous adjacently spaced obstructions having the size of single-family residential dwellings or larger.
- Exposure C: open terrain with scattered obstructions, including surface undulations or other irregularities which includes shorelines situated in hurricane-prone regions, flat open country and grasslands.
- Exposure D: unobstructed, flat areas exposed to wind flowing over open water for a distance of at least 1.61km. This exposure shall apply only to site subjected to the wind coming from over the water.

All cases of wind exposure category were considered to account for all location in Korea. However, exposure B was the most accurate for analysis of street tree in urban area.

Table 1. Parameters of common urban street trees in Daegu, Korea (Yoon et al., 2013)

Species	Height H (m)	Diameter at Breast Height D (cm)	Linear Regression Equation D (cm), CA (m^2)
Acer buergerianum	6.6 ~ 13.2	12.8 ~ 41.0	D = 0.22CA + 18.77
Ginkgo biloba	6.6 ~ 13.6	10.5 ~ 34.5	D = 0.28CA + 15.20
Platanus orientalis	8.1 ~ 15.5	22.8 ~ 48.2	D = 0.19CA + 28.23
Prunus yedoensis	4.6 ~ 12.6	12.3 ~ 48.2	D = 0.56CA + 11.87
Zelkova serrata	6.2 ~ 10.0	11.8 ~ 38.4	D = 0.23CA + 15.71

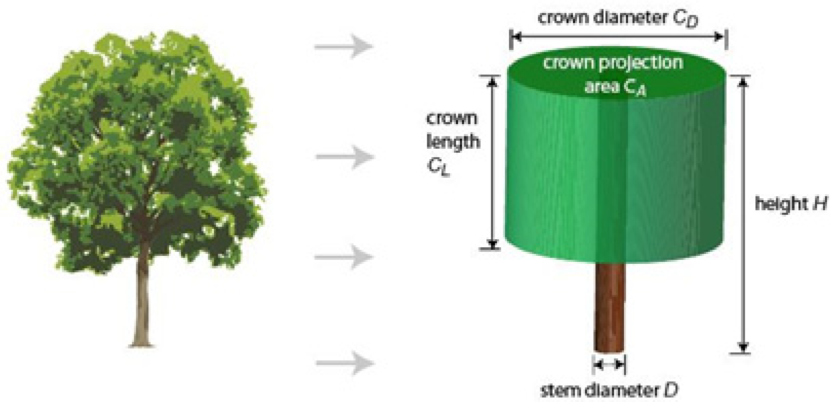

Fig. 2. Simple model represents each tree by a cylindrical stem and a cylindrical crown (image from http://formind.org/model/what-are-the-main-processes-of-formind/ growth/)

3. Statistical modeling of wind load

Wind load acting on tree was assumed to be static and could be determine based on ASCE-7 (2010) with the following equation:

$$F = 0.613 K_z K_{zt} K_d G C_f A_s V^2 \quad (2)$$

Where K_z is velocity pressure exposure factor depends on the height of tree, K_{zt} is topographic factor, K_d is wind directionality factor, and V is basic (3-second gust at 10m and in open terrain) wind speed in m/s, G is gust-effect factor, C_f is net force coefficient which depends on the external characteristics of tree, and A_s is gross area in m^2.

Normal distribution function was used to model these wind load parameters. The two parameters present the normal distribution were determined by Ellingwood and Tekie (1999) through Delphi questionnaire. By combining the two parameters with nominal wind load parameters in ASCE-7 (2010), the statistical wind load parameters used in this study were derived and presented in Table 2. Parameter K_z is height dependent, so the value was shown in range for the chosen tree height; parameter C_f is tree geometry dependent, thus it was also shown in range value.

4. Wind fragility modeling for tree

Wind fragility for tree presents the probability that the tree reaches their critical breaking resistance capacity in function of wind load or wind speed. This probability could be determined with a methodology presented by MCS as following:

$$P_f(v) = \frac{\Sigma_{i=1}^{N} (LS|\,V = v)}{N} \quad (3)$$

Where V is uncertain wind speed, v is a specific value of V (without uncertainty). Therefore, $\Sigma_{i=1}^{N}(LS|\,V=v)$ is the sum of tree reaching a limit state (LS) when wind speed equals v, and N is the number of simulations. LS in this study was the failure of tree, determined according to the comparison of critical breaking moment of tree in Korea proposed by Im et al. (2011) in equation (1) and probabilistic wind load generated based on equation (2).

Based on equation (2), probabilistic wind load acting on tree was randomly generated from their respective statistical parameters in Table 2. The basic idea of MCS was to use randomness to solve problems which have probabilistic interpretation. In this case of study, a large number of wind load W were generated, then compare with the resistance capacity R (critical breaking moment) of tree to determine their failure state. It could be presented as the following:

$$failure\,state = \begin{cases} R \le W & : fail \\ R > W & : safe \end{cases} \quad (4)$$

At each wind speed, 100,000 simulations were made and determined the tree's failure state based on equation (4). Then, the sum of total number of tree's failure could be determined. Subsequently, the probability of tree failure at each wind speed could be determined. Each wind speed was increased by 1m/s to get the best probability data points.

These probabilities of failure data points were fitted to lognormal cumulative distribution which is a widely used model to present fragility (Porter, 2015). Lognormal cumulative distribution function has the following form:

$$Fr(V) = \Phi\left(\frac{\ln(V/\mu)}{\sigma}\right) \quad (5)$$

In which, $\Phi(\cdot)$ is standard normal cumulative distribution function, μ is median capacity of the asset to resist damage, and σ is standard deviation of the natural logarithm of

Table 2. Summary of statistical wind load parameters

Parameters	Exposure	Mean-to-Nominal	Coefficient of Variation (COV)	Nominal	Mean	Standard Deviation (SD)
Kz	B	1.0143	0.1900	0.6491 ~ 0.6743	0.6584 ~ 0.6840	0.1251 ~ 0.1300
	C	0.9388	0.1400	0.9285 ~ 0.9550	0.8717 ~ 0.8965	0.1220 ~ 0.1255
	D	0.9655	0.1400	1.1094 ~ 1.1355	1.0712 ~ 1.0964	0.1500 ~ 0.1535
Kd	-	1.0471	0.1600	0.8500	0.8900	0.1424
Kzt	-	1.000				
G	B	0.9625	0.1169	0.8000	0.7700	0.0900
	C	0.9765	0.1205	0.8500	0.8300	0.1000
	D	0.9765	0.0843	0.8500	0.8300	0.0700
Cf	-	1.1000 ~ 1.5000				

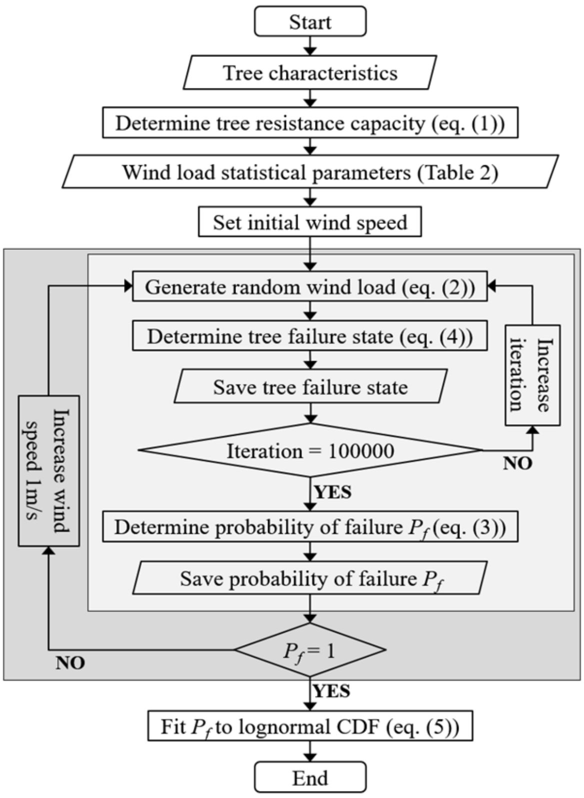

Fig. 3. Urban tree wind fragility development procedure

the capacity of the asset to resist damage. The two parameters μ and σ were used to present the wind fragility which can be used to integrate with other PRA framework to provide factual basis for disaster management or decision making (Vickery et al., 2006). The summarize of urban street tree's wind fragility development procedure was shown in Fig. 3.

5. Results and discussions

Wind fragility curves for all combinations of urban street tree characteristics chosen in this paper were presented in Fig. 4 where exposure category B was considered the urban area. The tree with height 8m and diameter at breast height 30cm had the highest probability of failure which illustrated by the median capacity of its fragility curve μ=38.70m/s. It means that at wind speed 38.70m/s, this tree had a 50% chance of failure. The tree with the highest resistance to wind load was the tree with height 7m and diameter 35cm. It had median failure wind speed 50.60m/s. For the same height tree, even though the tree with bigger diameter had more wind loading area, it had a higher critical breaking moment which resulted in their lower probability of failure. Furthermore, for tree with the same diameter, it was expected for the higher tree to have a higher probability of failure since wind load was depended on height. However, the four fragility curves showed that the diameter of tree was the dominant factor in their resistance against wind load. This trend can also be observed for wind fragility in exposure category C and D in Table 3. In Table 3, all parameters of wind fragility were presented for all cases chosen in this paper. They were classified by tree characteristics, i.e. height and diameter, and wind exposure category.

In Fig. 5, wind fragility curves for tree with height 8m and diameter 30cm were shown in all wind exposure categories. The urban tree, in category B, has the lowest probability of failure due to the urban area terrain help to reduce wind loading on the tree. The median failure wind speed for this case was 38.70m/s which classified as "typhoon" by the Typhoon Committee (2015). However,

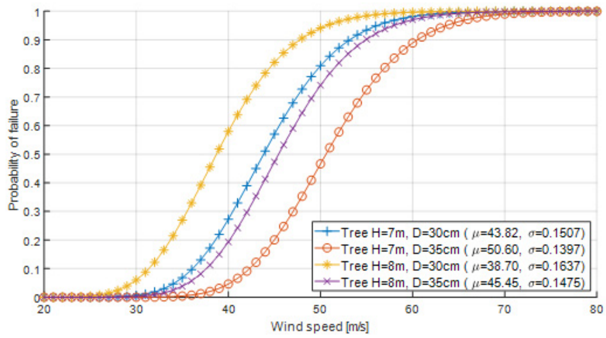

Fig. 4. Wind fragility for urban street tree in exposure category B

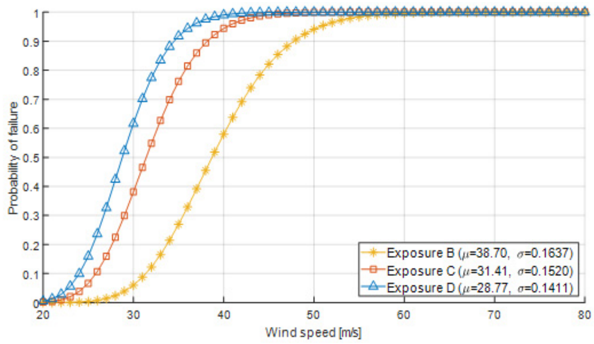

Fig. 5. Wind fragility for tree with height 8m and diameter 30cm in different wind exposure category

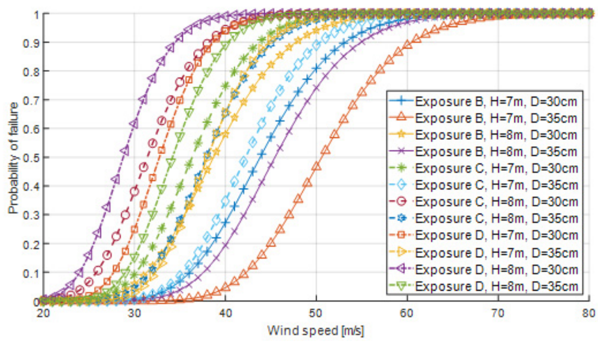

Fig. 6. Wind fragility for all cases of tree characteristics

Table 3. Wind fragility parameters of all cases of tree characteristics

Tree Characteristic \ Exposure Category		Exposure B		Exposure C		Exposure D	
H (m)	D (cm)	μ (m/s)	σ	μ (m/s)	σ	μ (m/s)	σ
7	30	43.8184	0.1507	36.3411	0.1441	32.7435	0.1291
	35	50.5959	0.1397	42.2256	0.1379	38.0282	0.1268
8	30	38.7046	0.1637	31.4137	0.1520	28.7685	0.1411
	35	45.4490	0.1475	37.8919	0.1373	34.1820	0.1275

for tree in open terrain, exposure C, and area where wind come from the open water surface, exposure D, their median capacity was only 31.41m/s and 28.77m/s, respectively. These wind speeds were classified as "severe tropical storm". This result showed that the urban tree, with the characteristics considered in this paper, had an expected probability of failure equal to 50% during the typhoon event. However, if the location of the tree was in a more exposed area, i.e. exposure C and D, they could only withstand sever tropical storm disaster level. To compare all cases considered in this paper, Fig. 6 shows all twelve combinations of tree's characteristics and exposure categories. They were classified by exposure category, tree height, and their diameter.

6. Summary and conclusions

Analytical wind fragility development concept for tree was presented in this paper. MCS method was used to generate a large number of random wind load applied to four types of tree differentiated by their height and diameter at breast height. The characteristics of tree selected in this paper were based on the typical tree found in urban area in Korea. Their resistance capacities were determined by the equation proposed based on the field tree pulling-test experiment. Although the proposed equation did not account for all species of tree found in urban area, it gave a better estimation of tree's resistance capacity in Korea. Even though the determination of wind fragility in this paper significantly depended on the estimation of tree resistance capacity proposed by other researchers, the probabilistic concept and method in this study can be flexibly updated or replaced with better experimental results for tree resistance capacity accounted for tree species found in the focused area.

With MCS technique, probability of failure for tree at a specific wind speed was found. The increment of wind speed in this study was chosen at 1m/s. Subsequently, the data points of probability of failure at all wind speeds were fitted to lognormal cumulative distribution function with two parameters μ and σ. These two parameters presented the wind fragility for the type of tree chosen in this paper. The results of these parameters can be used to integrate with a larger database of probabilistic risk assessment to help improving the disaster manage decision making. Results found in this paper showed that among the four types of tree chosen, the tree with height 8m and diameter 30cm had the highest probability of failure. The median failure capacity of this tree in the urban area, i.e. exposure B, was 38.7m/s. Furthermore, it was found that the diameter of tree was the dominant characteristic to determine their survivability under wind load. In urban area where the tree was protected by other assets or structure, their median capacity was bigger comparing to their counterpart in the open terrain, i.e. exposure C and D.

The failure of tree in urban area not only damages the country's economic, but also causes harm or disruption to people's lives during the extreme wind events. Research on the improvement of safety for urban tree or urban forest should increase to similar level as the other public structures. Moreover, experiment for all species of urban tree should be conducted, since their performance behavior can be very difference from one another based on their many characteristics and their root interaction with soil. With better understanding of each tree species, the reliability in the prediction of their performance can be greatly improved.

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