doi:10.5937/jaes17-22021 Paper number: 17(2019)4, 628, 443 - 448

VALIDATION OF STRENGTH AND FLEXIBILITY OF SENGON (PARASERIANTHES FALCATARIA) BY EXPERIMENTAL TREE-PULLING TEST AND NUMERICAL SIMULATION

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Stability assessment of trees is considered important in urban areas to detect possible occurrence of tree failures that often result in disastrous damages. Tree-pulling test is a low-cost, well-known method that has been practiced by researchers and practitioners alike from several decades ago. From the method, a number of parameters related to the physical characteristics of the tree can be further derived. However, the tree-pulling test has only been widely practiced mostly for tree species in subtropical region, such as pines, spruces, and birches. In this paper, a tree-pulling test on sengon (Paraserianthes falcataria), a tree native to Indonesia is reported. Such a study is imperative as sengon is among the most commonly planted tree species in the urban areas of Indonesia and there have been alarming reports of falling sengon trees. Two kinds of tree-pulling test are conducted. i.e. destructive and non-destructive. From these experiments, the critical force that results in a breakage as well as the flexibility of sengonare obtained. Numerical simulations are also carried out. The results arecompared and they show a good fit to the experimental data, justifying the assumed linearly elastic behavior.

Key words: tree-pulling test, structural strength, deflection, Paraserianthes falcataria

INTRODUCTION

Incidents of falling trees in urban environments are hazards that often result in significant damages to people or properties. It is a matter of serious concern, especially for some urban environments surrounded by a massive population of planted trees, such as several universities in Indonesia. In fact, there have been several cases of tree failures resulting in loss of life in the campus of Universitas Indonesia in Depok. It is therefore imperative for officials in charge to conduct a frequent tree stability assessment as a means for recognizing the risk that may arise.

A number of methods for such a purpose have been adopted worldwide. Besides the well-practiced yet inadequate visual inspection, the use of a more advanced acoustic tomography [1-3], ultrasonic tomography [4-5], have also been reported. Another widespread assessment method is the tree-pulling test which dates to several decades ago. Fraser (1962) is known to be among pioneers that first reported the method and it has been practiced ever since.

The method is considerably simple without the need of any complex instruments, yet it provides a means to study the mechanism associated with failure of trees [e.g. 6]. Owing to its simplicity, the tree-pulling test is arguably well-suited for being implemented in most developing countries that need a method which is technically and economically practical. Besides, the importance of the tree-pulling test is also evident since many useful outputs are attainable, such as the data on the critical force that causes a breakage or an uprooting, the failure mode of a tree, among others. The critical force, for example, is commonly utilized for understanding the physical characteristics of the tree, e.g. resistive bending moment, modulus of rupture (MOR), modulus of elasticity (MOE) [7-8], as well as flexibility [9]. The data could also be extended further via analytical calculation to predict the risk of a wind [10-11] or used for numerical simulations [12-15], as they are widely deemed as a useful, inexpensive alternative to studying the failure mechanism of trees.

It is worth-noting, however, that despite the widespread implementation of the tree-pulling test, most researchers only applied it to trees from subtropical region, e.g. pine [8, 16-18], spruce [8, 19-21]; and birch [8]. Only a few had implemented the test on tropical trees, such as Samanea saman [22-25], Aglaia and Nephelium [26], Vitellaria paradoxa [27], Eugenia grandis [28] whereas to the best of our knowledge, none had tried it on Paraserianthes falcataria, a tree native to Indonesia, which is locally known as sengon. The analysis on sengon is crucial, especially considering its massive population in some urban areas in Indonesia.

In this research, the objective is to conduct a tree-pulling test on sengon which results in deflection graphs of the tree. The focal point of the analysis is on the critical force for a breakage to occur as well as the flexibility of the tree. As for the latter, the experimental data will be compared to that obtained via numerical simulations for validation. Via this endeavor, we hope that the resulting data will serve as an introductory means to understand the characteristics of sengon tree under a static load.

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MATERIALS AND METHODS

Sengon treeand experimental method

Sengon (Paraserianthes falcataria), is considered as one among many important tree species in diverse areas in Indonesia. Being a fast-growing tree species with its ability to grow on a variety of soil conditions, sengon is known to play an important role in both commercial and traditional farming systems by smallholders. Its commercial uses are mainly for the pulp and paper as well as the furniture industry. Additionally, the wood is also commonly used for light construction and other general purposes. Sengon is a large tree that can grow up to 40 m tall with a straight bole. The buttress is small or absent [29].

In this research, sengon trees in the campus of Universitas Indonesia are the object of study. The selection of sengon, of other possible options, was based on the inputs from the Occupational Safety, Health and Environmental (OSHE) Unit Universitas Indonesia whom we collaborated with for the completion of this research work. First, sengon has a large population in the campus of Universitas Indonesia. Owing to its fast-growing characteristic, sengon was chosen and massively planted early during the development of the Depok campus during the 1980s. Second, based on the recorded data from the OSHE unit, sengon is the tree species with the third most cases of falling incidents in the campus area, trailing behind sengonbuto (Enterolobium cyclocarpum) and flamboyant (Delonix regia).

The tree-pulling experiments to two sengon trees were conducted in the campus of Universitas Indonesia. Fig. 1 below shows the photograph of one of the sengon trees that had been studied. The trees were three years old at the time of the experiment. The geometry of the two trees, named tree A and B, i.e. the height and DBH (diameter at breast height) is given in Table 1. Two trees with nearly identical geometrical parameters were selected. The trees were also visually-inspected prior to the experiment and was identified as healthy.

Figure 1: Photographs of the sengon for tree-pulling test

Table 1: Geometrical parameters of the sengon for tree-pulling test

Tree	Height, *H* (m)	DBH (cm)
A	±20	24.5
B	±20	24.8

The schematic of the experimental set up is depicted in Fig. 2. For carrying out the tree-pulling test, several equipment were used, i.e. kernmantle rope, digital weighing unit with a maximum measured load of 500 kg, manual hand winch, and a conical pendulum. Recorded data were the pull force (F) from the digital weighing unit, and the deflection magnitude of the pulled tree, δ, measured with the aid of the dangling conical pendulum. Recorded control variables were the height of the attachment point from the ground, h, and the distance between the pulled tree and the adjacent support tree, d, which functions as the anchorage point of the rope. The two control variables allowed for the calculation of the lateral pull force, Fcosθ. The height of the attachment point, h, was 12.23 m and 12.20 m for tree A and tree B, respectively.

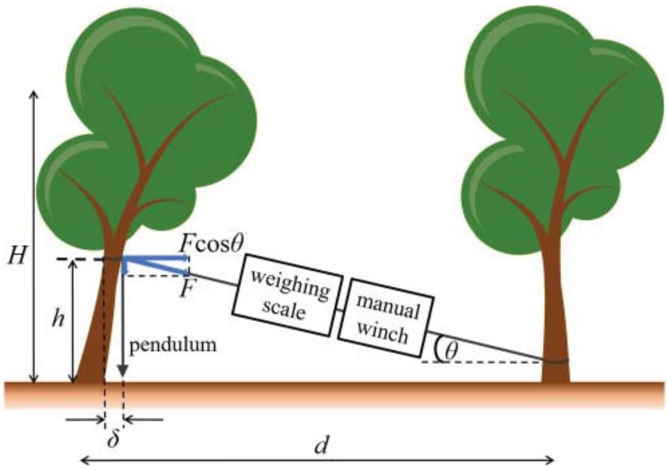

Figure 2: Schematic of the experimental tree-pulling test (not to scale)

The tree was pulled sideways under calm conditions, and each data was recorded after every 1.5 m of pulling of the winch. In total, there were two trees, tree A and tree B, pulled in experiments of different purposes. In the first experiment, tree A was pulled until breakage occurs, i.e. destructive tree-pulling test, from which an information on the critical force was obtained. Subsequently, the second experiment was a non-destructive test to tree B in which the pulling was carried out with a force less in magnitude than the previous experiment, so as to not cause the tree to enter the plastic region of deformation [6]. From the second experiment, a deflection graph resulted from the applied force could be obtained, and further calculation of its slope would allow us to get the value of flexibility [9] of sengon trees.

Data analysis

From the experiments, the main outputs are deflection graphs that show the relationship between the lateral pull force applied, Fcosθ, and the deflection, δ. Upon pulling, the tree's stem was assumed to deflect while maintaining its straightness with a negligible bending. Therefore, the calculation of the angle θ was made simplified. For the second experiment, the flexibility data was obtained by using the linear regression method applied to the various experimental tree-pulling data. The intercept at zero force condition is taken as the displacement origin. Assuming small deflection and conventional elastic behavior of the tree, the slope of the fitted line could be considered as the flexibility (the reciprocal of stiffness) in cm per Newton [9].

FEM Simulation method

FEM (finite element method) numerical simulations were carried out mainly to validate the data obtained via experimental tree-pulling test. A commercial FEM software ANSYS with static structural analysis was used for the simulation. As mentioned in the previous section, the sengon tree in general has a straight bole. The tapering is generally identified mostly in the upper portion of the stem [30]. In this experiment, as the rope attachment was made at slightly over the midway point of the stem's height, it is tolerable to model the sengon tree as a non-tapered cylindrical cantilever beam with a static lateral load applied to the tip of the free-end. Assuming negligible bending, the whole pulling process of the sengon tree could well be predicted to bear resemblance to the simple deflection of a cantilever beam. Therefore, the linearity between the deflection and the applied lateral force shall be expected.

The height of the models followed the measured data from the experiment. As for the material properties, the modulus of elasticity and density from the work of Marsoem et al. [31] (Table 2) were set to the models.

Table 2: Geometrical parameters of the sengon for tree-pulling test

Modulus of elasticity	3583.86 MPa
Density	300 kg/m3

As an additional note, the effect of the crown must also be discussed prior to presenting the results obtained. It has been widely argued that during the pulling test, the crown can possibly contribute to an additional overturning moment to the tree [6, 23], and this is a function of the crown's volume. As such, incorporating the crown's volume in the modeling for simulation shall be considered. However, it is also well understood that measuring the crown's volume is a difficult endeavor. In this research, therefore, the crown's volume was not incorporated in the modeling of the tree. Upon presenting the results, this note on the crown shall be discussed again in the later part of this paper.

Results and discussion

From the tree-pulling test to tree A, the resulting graph of deflection is given in Fig. 3(a).

Figure 3: (a) deflection graph of tree A, (b) photograph of the breakage in tree A, (c) deflection graph of tree B with two trials of tree-pulling test without breaking the tree

The critical force of 2256 N was recorded which resulted in a deflection of 263 cm before the breakage occurred. The height of the breakage point on the stem (Fig. 3(b)) was measured to be ±2.7 m from the ground level. Fig. 3(c), on the other hand, depicts the results of the second experiment on tree B which involves two times of pulling process, i.e. 1st trial and 2nd trial. Each trial underwent a pulling of up to 1622 N. It can be clearly inferred from the graph that the slope of the both trials are identical, corresponding to a similar value of flexibility. However, a shift of the graph upward is also noticeable. According to Sani et al. [6], at a bending inclination of 2.5^o to 4^o, a tree has already undergone a transition from elastic to plastic state. During the 1st trial of tree-pulling test on tree B, the maximum deflection of 145 cm had occurred, and this corresponds to a bending inclination of 6.7^o. This fact may justify the shifting of the graph; that the transition to plastic state had occurred and this contributes to the shift of the graph during the 2nd trial.

To better comprehend the results obtained, simulations were carried out as a means of validation as well. The whole results are shown in Fig. 4 and Fig. 5. Fig. 4 shows the simulation results plotted with the experimental data of tree A in the same graph. The differences in deflection values between the experimental and simulation were calculated for each steps of the experimental lateral pull

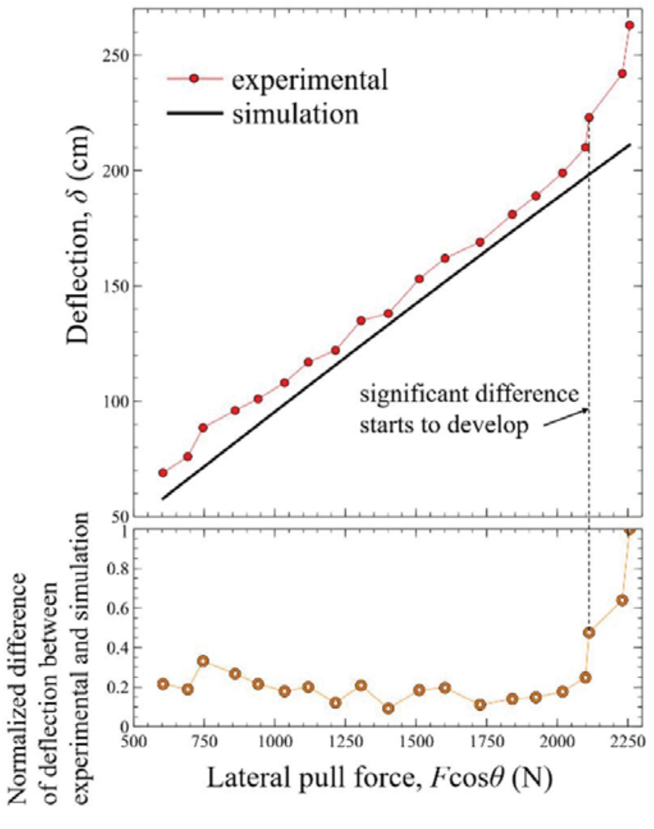

Figure 4: Deflection graph of tree A plotted with corresponding result of numerical simulation. Below graph shows the difference between the experimental and simulation values normalized by the maximum difference value

force. The results were then divided by the maximum value of the difference and were termed as the normalized difference of deflection between experimental and simulation. This data was plotted alongside in Fig. 4 to show how much the deflection values differ between experimental and simulation from the start of the tree-pulling test until the breakage occurs.

When examined, the experimental data initially looks to have a slope of an identical value to that of the simulation. However, after a certain point, or when the lateral pull force reaches 2112 N, the slope becomes steeper, corresponding to a larger value of the normalized difference of 0.47. This point could be reasonably perceived as the beginning of the major plastic deformation occurring on the stem which eventually leads to the breakage. Beyond this point, the normalized difference becomes larger until reaching the value of 1. This observed phenomenon of steeper slope approaching the point of breakage is consistent with the theoretical understanding of the breakage of a cantilever beam and was also reported by Sani et al. [6].

Subsequently, all deflection graphs from the experimental tree-pulling test of tree A and tree B were fitted with linear regression method. For tree A, only the data before the occurrence of the perceived plastic deformation was considered for inclusion of the linear regression. The graph of simulation was also plotted and the combined graphs are shown in Fig. 5.

Several observations can be made from Fig. 5. First, the flexibility of sengon tree, represented by the slope of the

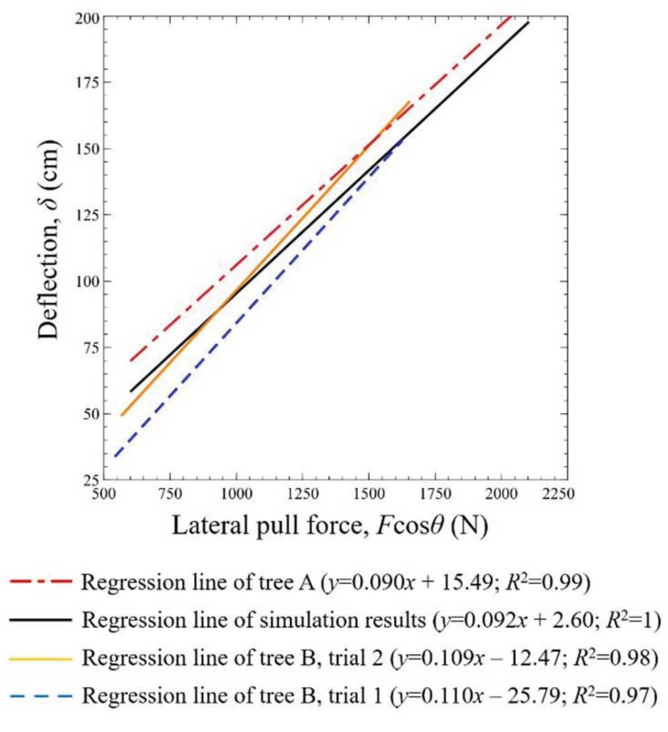

Figure 5: Regression lines of experimental data of tree A, tree B trial 1, and tree B trial 2, plotted with that of simulation results

Journal of Applied Engineering Science Vol. 17, No. 4, 2019
ISSN 1451-4117

graphs, shows identical values with arguably small error. Averaging all four values gives flexibility of 0.100 cm/N with standard deviation of 0.0092 cm/N. Alternatively, taking into account the differences between tree A and B, we could also account for separate flexibility value of 0.090 cm/N and 0.109 cm/N for tree A and B, respectively. The difference in values between tree A and B, which corresponds to 21.7%, is arguably attributed to some factors beyond the scope in this research, primarily differences in morphology or in soil conditions between tree A and B. These factors might strongly play a role in determining the flexibility of a tree and therefore shall be considered in the future endeavor. In contrast, the difference of 21.7% could also be well-reasoned to be within an acceptable margin of error that justifies the repeatability of tree-pulling test on sengon trees. With regard to the flexibility value itself, a comparison can be made with that of Sitka spruce obtained by Neild et al. [9]. The research by Neild et al. [9] exhibits some similarities to this research; besides making use of Sitka spruce, another tree species with a straight bole, as the object, the study also attached the rope at the height of >10 m on the stem. The reported flexibility values are in the range of 0.174 to 0.439 cm/N for three different trees. The values are noticeably in the same order of magnitude as that of sengon trees in this research, with differences that may come from the morphological factors, such as the DBH (Sitka spruces have larger ones).

Second, the assumed linearly elastic behavior is justified by the high degree of fitting indicated by the R^2 values as remarked in Fig. 5. Regression line of tree A, tree B 1st trial and tree B 2nd trial each has R^2 values of 0.99, 0.97, and 0.98, respectively. This finding shows that the neglect of the bending of the stem as well as the crown effect is justified.

CONCLUSION

Experimental tree-pulling test to two different sengon trees and numerical simulations corresponding to each test were carried out. The critical force that resulted in a breakage was 2256 N. Subsequently, the slopes of the deflection graphs were obtained by the linear regression method and were compared to those obtained via numerical simulations. The results from numerical simulations show a good fit, justifying the linearly elastic behavior of the pulling of sengon tree that had been assumed beforehand. The obtained flexibility values were 0.090 cm/N and 0.109 cm/N, for tree A and tree B, respectively.

ACKNOWLEDGEMENT

This work was funded by Hibah PTUPT Kemenristekdikti fiscal year 2018 (512/UN2.R3.1/HKP05.00/2018). We are also grateful to the help of Prof. dra. Fatma Lestari, M.Si., Ph.D and Dr.Anom Bowolaksono, MSc. of Occupational Safety, Health and Environmental (OSHE) Unit Universitas Indonesia for their support during the experiments.

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Paper submitted: 06.06.2019.
Paper accepted: 03.10.2019.