# 3D RISK MAPPING OF HAZARD TREE IN CHANGDEOKGUNG PALACE

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**KEY WORDS:** Risk prediction, Tree failure, Tree falling down, Impulse, Potential failure zone, Heavy old tree, Disaster.

**ABSTRACT:**

This study aimed to draw up a risk map of predicting the potential failure zone and impulse that may occur due to the fall of trees in the palace. The main findings of the study are as follows. First, a formula for calculating a failure zone and impulse that would occur in the fall of trees was established. The potential failure zone was calculated with the internal range of a circle with a radius of 1.5 times the height, reflecting the possibility of a tree falling and slipping. Second, employing Rhino3D and Grasshopper algorithms for calculating the failure zone and impulse were developed. It was designed, considering rearing information, such as tree height and weight, and the adjacent trees and terrain. Third, tree risk maps were produced in the areas of Yeongyeongdang Hall and Aeryeonjeong Pavilion in Changdeokgung Palace. In the tree risk map, the impulse and failure zone were marked, expected for the buildings and terrain against which trees collide when fall. It was possible to understand the space and trees with great impulse and high possibility of risk in advance through this. This study has significance in that it proposed methods for quantifying and predicting the potential failure zone and impulse occurring in the fall of trees. Assessing the trees accompanied by a lot of damage since they have a wide failure zone would make efficient management possible. In addition, it can be utilized for the establishment of countermeasures for disaster prevention and as baseline data for the safety of the surrounding cultural heritage and visitors.

## 1. INTRODUCTION

At Changdeokgung Palace, a World Heritage Site, trees shape the natural landscape, providing greenery, landslide protection, and noise reduction. However, over time, they grow large and become vulnerable to disease and decay. In this condition, they may break or fall due to external factors such as heavy rain and typhoons, or internal damage. Falling trees can cause damage to historic buildings and visitors. In recent years, climate change such as rising temperatures, increased precipitation, and changes in season lengths have led to an increase in tree failures. In particular, a tree falling has a wide range of damages and high impact, so it is urgent to prepare a proactive management plan instead of a reactive recovery.

Local governments of Korea are implementing projects to remove hazardous trees to prepare for risks caused by trees. However, there is a lack of clear criteria and evaluation of hazardous trees. This is inefficient and may cause damage to the landscape and natural environment, as even trees that are not likely to pose a real risk or have minor damage which can be mitigated through pre-management may be removed.

Guyon et al. (2017), Angwin et al. (2012), and Lee et al. (2020) conducted studies to address the risk due to tree failure. These studies calculated the potential failure zone where damage can occur and graded the risk by determining the likelihood and degree of damage. However, they did not produce specific physical quantities of risk, and the criteria for judgment were vague and not quantitative.

If it is possible to quantitatively calculate the falling of trees, it will be possible to rationally determine the hazardous trees and areas that need priority management and contribute to protecting the lives of historical buildings and visitors. Therefore, this study aimed to create a tree risk map that predicts the potential failure zone and impulse caused by a tree falling in the palace.

## 2. MATERIALS AND METHODS

This study was conducted as follows.

First, to quantitatively calculate the risk of a tree falling, this study proposed the potential failure zone and impulse calculation formula through theoretical review. The potential failure zone is the physical range in which damage can be caused by a hazardous tree, and the impulse is the physical amount applied to the surrounding area due to the falling of a hazardous tree.

Second, this study developed an algorithm to calculate the potential failure zone and impulse and visualize them. To create a three-dimensional model to analyze the risk in three dimensions, this study used Rhino3D, which allows free curved surface modeling. The algorithm was developed using Grasshopper, a plug-in for Rhino3D.

Third, this study verified the feasibility of the tree risk calculation algorithm by creating a tree risk map for Changdeokgung Palace in Korea. Changdeokgung Palace is a UNESCO-listed World Heritage Site and is a combination of architecture and landscape, with old trees growing around the building. A three-dimensional model of Changdeokgung

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Palace and its surroundings was created and a simulation of tree falling was conducted to predict the risk.

# 3. RESULT AND DISCUSSION

## 3.1 Deriving the Risk Formula

### 3.1.1 Potential failure zone

The potential failure zone is the physical and potential range of damage that can occur when a tree falls. The larger the potential failure zone, the more damage a falling tree can cause. This is calculated by considering terrain, height, and whether the tree is upright or not.

Lee et al. (2020) state that the potential failure zone of a tree growing on flat ground is the area inside a circle with a radius of 1.5 times its height. This takes into account the possibility of slipping or blowing away as the tree falls. Trees growing on slopes may have a larger sliding range than on flat ground. Guyon et al. (2017) applied a slip margin (0.5 times the height) to the potential failure zone to account for the distance a tree on a slope would slide or roll down as it falls. When calculating the slip margin, the roughness coefficient should be taken into account through careful study.

However, considering the frequently changing terrain due to climate and seasonal changes, planting, and removal of herbal plants, it is not practical to measure the roughness coefficient because it is time-consuming and costly. As this study is a rudimentary step in experimenting with the feasibility of quantifying and visualizing the risk posed by falling trees, it did not reflect a roughness coefficient. Instead, a potential failure zone was set with a radius of 1.5 times the height to account for the possibility of a tree falling and sliding.

In addition, the tilt of the tree is an important factor in calculating the potential failure zone, as the potential failure zone is calculated differently depending on whether the tree is upright or not (Figure 1). For upright trees, the potential failure zone was set at 360° around the root of the tree. Leaning trees are considered to be at risk of falling if the center of gravity deviates from the root, and trees leaning more than 15° are at risk of falling, while those leaning 10° or less are considered to be at relatively low risk of falling (Kim, 2021). In this study, trees that lean more than 5° from the upright position were identified as having a high risk of falling, and the impulse of potentially falling trees was also predicted. Guyon et al. (2017) set the potential failure zone of leaning trees as a half circle from the leaning direction to a point at 90° left-right. Based on this, this study drew an arc of 90° from the leaning direction to the left and right and set 180° as the potential failure zone.

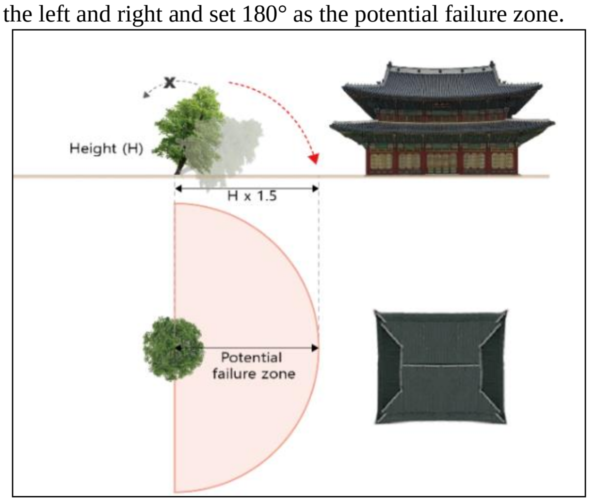


**Figure 1**. Example of calculating the potential failure zone of trees growing at an inclination

### 3.1.2 Impulse

In the case of a tree falling, it is necessary to calculate the specific physical force exerted on the target along with the potential failure zone. This physical quantity is called impulse, and the unit is N-s or kg-m/s. By calculating the impulse generated by a tree falling, it is possible to quantitatively and objectively determine the hazardous trees and objects that need to be managed first.

The speed at which a tree falls has a significant impact on the impulse. Even if the shape, height, and weight of a tree are similar, many variables such as branch and leaf density, failure, wind speed, and air resistance can change the speed of falling. However, it is impossible to take all these variables into account at any given time. Therefore, in this study, the impulse was calculated by controlling the study environment (Table 1). Height, weight, angular velocity, and angular acceleration were set as independent variables, and the impulse was set as the dependent variable.

Even if the height and weight are similar, the shape varies depending on the density of branches and leaves, and the weather conditions that encourage failure affect the speed at which the tree falls. To reflect these field conditions, this study is a basic theoretical study, and leaf volume, tree failure, external force, and air resistance, which affect the calculation of impulse, are set as control variables. In addition, to simplify the calculation of the impulse, the tree is assumed to be a rigid body that does not deform in size or shape due to external forces.

| Classification | Variables |
|---|---|
| Independent variables | Height, weight, angular velocity, angular acceleration |
| Dependent variable | Impulse |
| Control variables | Leaf volume, tree failure, external force (wind pressure, etc.), air resistance |

**Table 1**. Variables for calculating impulse

The impulse ($F$) is interpreted as the change in linear momentum ($\Delta p$), which is the aftermath momentum ($mv_2$) minus the initial momentum (($mv_1$) (Equation 1). Applying this to the situation where a tree falls, the initial momentum of the tree before it falls is zero, and the aftermath momentum is the momentum just before the impact is applied. In other words, the impulse applied to the tree when it falls is the same as the aftermath momentum just before the impact is applied.

$$F = \Delta p = \mathrm{mv}_2 - \mathrm{mv}_1 \quad (1)$$

When a tree falls, it rotates around the point of falling and generates angular momentum. Angular momentum ($L_t$) is calculated as the product of the moment of inertia ($I_t$) and angular velocity ( ω ). The moment of inertia ( $I_t$ ) is the magnitude of the force with which a rotating object tries to maintain its rotation, measured in kg·㎡. To calculate the moment of inertia of a falling tree, the moment of inertia of a rod rotating past the end of an axis was utilized. In other words, the moment of inertia ( $I_t$ ) that occurs when falling was calculated by dividing the weight of the tree (M) multiplied by height$(\mathrm{L})^2$ by 3 (Equation 2).

$$I_t = \frac{1}{3} M L^2 \quad (2)$$

Angular velocity (ω) is the change in angular position ($d\theta$) of a rotating object divided by the unit time ($dt$), using rad/s as the unit. The angular acceleration (α) is the change in angular velocity (dω) per unit time ($d$t ), in rad/$s^2$ (Equation 3).

$$\omega = \frac{d\theta}{dt} \alpha = \frac{d\omega}{dt} \quad (3)$$

To calculate the angular velocity of a falling tree, it is necessary to consider time. However, it is very difficult to calculate the time when a tree falls because it is affected by various factors such as shape and leaf shape, leaf volume, and the cause of falling. Therefore, to derive angular velocity using items other than time, substitute unit time for angular velocity and angular acceleration, and the relationship in Equation (4) is established.

$$\omega\, d\omega = \alpha\, d\theta \quad (4)$$

In Equation (4), the angular velocity is integrated over the initial angular velocity and the impact angular velocity (Equation 5). The initial angular velocity ($\omega_i$)) is zero at the time the tree falls, and the impact angular velocity ($\omega_f$) is the angular velocity just before the tree falls and affects the target. The angular acceleration was integrated over the initial angle and the impact angle. The initial angle ($\theta_i$) is the tilted angle at the time the tree falls, and the impact angle ($\theta_f$) is the tilted angle at the time the tree affects the building or ground.

$$\int_{\omega_i}^{\omega_f} \omega\, d\omega = \int_{\theta_i}^{\theta_f} \alpha\, d\theta \quad (5)$$

The angular acceleration (α) was derived by substituting the equations that calculate the torque (τ ), $\tau = rF\sin\theta = \frac{1}{2}\mathrm{Mg}\sin\theta$ and $\tau = I_t \times \alpha = \frac{1}{3}ML^2 \times \alpha$ (Equation 6).

$$\frac{L}{2} Mg\, sin\theta = \frac{1}{3} ML^2 \times \alpha \quad (6)$$

$$\alpha = \frac{3g\, sin\theta}{2L}$$

Substituting the angular acceleration ( $\alpha = \frac{3g\, sin\theta}{2L}$ ) into Equation (5), the impact angular velocity ($\omega_f$) was calculated (Equation 7).

$$\int_{\omega_i}^{\omega_f} \omega\, d\omega = \int_{\theta_i}^{\theta_f} \alpha\, d\theta \quad (7)$$

$$\left[\frac{1}{2}\omega^2\right]_{\omega_i}^{\omega_f} = \int_{\theta_i}^{\theta_f} \frac{3g\, sin\theta}{2L} d\theta$$

$$\frac{1}{2}\left(\omega_f^2 - \omega_i^2\right) = \frac{3g}{2L}\left[-cos\theta\right]_{\theta_i}^{\theta_f}$$

$$\frac{1}{2}\omega_f^2 = \frac{3g}{2L}\left(-cos\theta_f + cos\theta_i\right)$$

$$\omega_f^2 = \frac{3g}{2L}\left(cos\theta_i - cos\theta_f\right)$$

$$\omega_f = \sqrt{\frac{3g}{L}\left(cos\theta_i - cos\theta_f\right)}$$

In other words, the angular momentum ($L_t$) generated when the tree falls was calculated by multiplying the moment of inertia ($I_t$) and the impact angular velocity ($\omega_f$)) (Eq. 8).

$$L_t = I_t \times \omega_f \quad (8)$$

$$L_t = \frac{1}{3} ML^2 \times \sqrt{\frac{3g}{L}\left(cos\theta_i - cos\theta_f\right)}$$

Since the impulse is the change in linear momentum ($\Delta p$), the calculated angular momentum ($L_t$) must be converted to linear momentum. Therefore, impulse ( $P_t$ = linear momentum) generated when a tree falls is calculated by dividing the angular momentum ($L_t$) by the distance (D) from the rotation point to the impact point (Eq. 9).

$$P_t = \frac{L_t}{D} \quad (9)$$

When a tree falls, the weight of the affected object is the weight at ground level, which has a significant impact on the impulse. The above-ground weight (M) of a tree is calculated by using volume (3.14×(DBH) $(B)/2)^2$ ×height(L)), tree shape coefficient (K), unit weight (U), and complementarity of branches (P), and the unit is kg.

In general, in forestry and landscape construction, height is applied to calculate the weight of the aboveground part of the tree. However, when calculating the impact caused by falling, the impact point is the same or shorter than the height. In addition, the impact may be cascaded over multiple points during the falling process. Therefore, the distance (D) from the point of rotation to the point of impact is taken into account when calculating the weight of the ground part for calculating impulse, not the height. A coefficient of variation of 0.5 is used when it is difficult to define or measure. The unit weight is 1300 kg/㎥ for shrubs and 1200 kg/㎥ for trees, and the complementarity rate (p) due to the refreshment of branches is 0.1 for shrubs and 0.2 for forest trees. Considering this, the aboveground weight of the tree was calculated (Equation 10).

$$\mathrm{M} = 3.14 \times (B/2)^2 \times D \times K \times U \times (1 + p) \quad (10)$$

### 3.2 Development of risk calculation algorithm

The algorithm for calculating the risk of a tree falling consisted of creating a 3D model, calculating the tree risk, and visualizing the calculation results.

#### 3.2.1 Creating a three-dimensional model

A three-dimensional model was created to build spatial information for risk calculation. Trees, terrain that could be damaged, and building models were created. The terrain and building models were created in Rhino3D as surface models. For accurate and efficient risk calculation, the surface model was created in the form of a mesh with evenly spaced grid points using Grasshopper.

The spacing of the grid points in the mesh was adjusted to account for the geometry of the object. The tree model was created by considering the growth position, height, and slope. To make it easier to adjust the shape to reflect the growth status, it was made in the form of a line with two endpoints. The information from the line was connected to Grasshopper to realize a tree-like shape. The model was used to map the potential failure zones and impulse calculations to visualize the degree of risk.

### 3.2.2 Development of potential failure zone calculation algorithm

The potential failure zone calculation algorithm was coded in the following steps: initial value setting, potential failure zone calculation, and risk inquiry.

In the initial value setting stage, the terrain, building, and tree models were connected to Grasshopper to build spatial information of the target area. When calculating the potential failure zone, the analysis range was set and calculated because it is efficient to analyze the space where the damage is expected to be fatal. The scope of analysis was selected as the area with a high occupancy period and frequency of use. To calculate the potential failure zone, this study first analyzed information such as the location, height, and leaning direction of the tree, and then calculated the falling radius.

The calculation of the potential failure zone is shown in Figure 2. The falling radius is the potential failure zone calculated as 1.5 times the height, and then the potential failure zone (Ai) is adjusted to reflect the inclination of the tree. For upright trees, the potential failure zone (Ai) was adjusted to 360° around the root, and for leaning trees, the potential failure zone was adjusted to 180° based on the wind direction. To improve the accuracy of the calculation, a fall line (L) was created within the potential failure zone (Ai). This is a horizontally rotated radiation (Ray) that starts at the root of the tree and is rotated at 1° intervals around the area where damage could occur. For upright trees, 360 rays were generated, and for leaning trees, 180 rays were generated in the direction of the plume. The presence of adjacent trees (Sk) within the potential failure zone (Ai) mitigates or prevents falling. In other words, the potential failure zone (A), where damage due to falling can occur, was calculated by subtracting the potential failure zone (Ai) calculated by considering height and tilt from the potential failure zone (Ai), where falling does not occur due to adjacent trees (B) (Figure 3). This process was repeated for the number of adjacent trees (p).

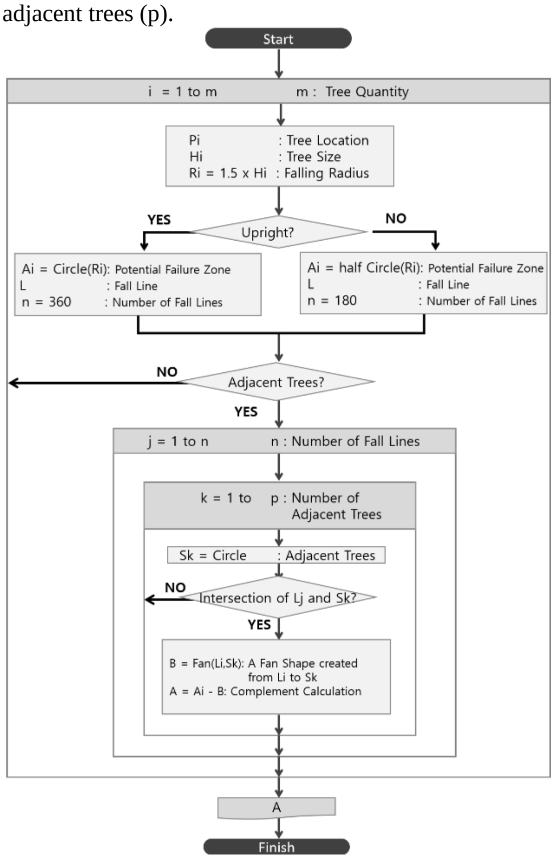


**Figure 2.** Potential failure zone calculation process

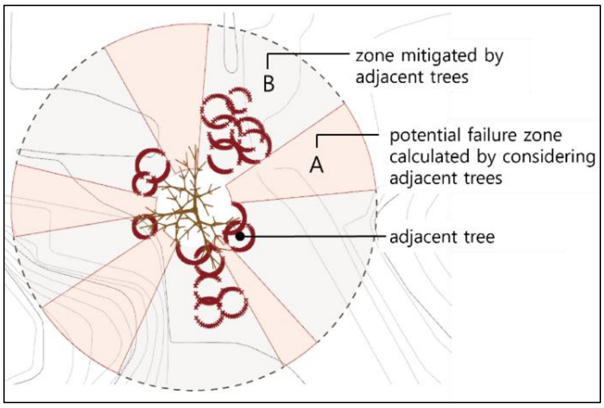


**Figure 3.** Potential failure zone calculated by considering adjacent trees

In the risk inquiry stage, the potential failure zone was calculated as an area, and the relative difference was visualized by aggregating them. Trees with large potential failure zones are colored red, and trees with relatively small potential failure zones are colored purple.

### 3.2.3 Development of Impulse Calculation Algorithm

The impulse calculation algorithm was coded in the following steps: initialization, impulse calculation, and risk inquiry.

In the initialization stage, the analysis range, terrain, building, and tree models were connected to Grasshopper. For tree models, information such as growth location, height, slope, pivot point (Pi), weight, and potential failure zone were reflected. The center of rotation (Pi) was set to the root to reflect the shape of a falling tree. The weight of the tree was calculated as the weight of the ground part corresponding to the main impact area in the event of falling. When calculating the weight, the input values such as height, diameter at breast height (DBH), unit weight of the trunk, and the complementary ratio of branches were set to be adjustable to reflect the output conditions of the tree.

In the impulse calculation step, this study utilized equation (9) and proceeded with the process shown in Figure 4. The extent to which falling is mitigated by adjacent trees was excluded from the calculation. To determine the collision with buildings and terrain when a tree falls, and to derive the point where the collision occurs first, the RP was generated. RPs were generated by creating perpendicular rotation planes at 1° intervals in the direction of the tree's fall (Figure 5). Horizontal fall lines were generated at 1° intervals within the potential failure zone. In the event of a collision between the tree and the target, the angle and impact coordinates (i_Loc) of the collision point were derived, and the impact distance (i_dist) was calculated. The impact distance (i_dist) is the distance between the center of rotation and the impact coordinate (i_Loc) where the tree hits the target. If the impact distance is shorter than the height, the possibility of an *n*th impact was considered for the part (Ri) that subtracts the impact distance from the height. In case of *n*th impact, the impact distance was accumulated and calculated repeatedly until it became larger than height, and the impact status, impact point, and impulse were calculated.

In the risk inquiry step, the impulse entered in the impact coordinates was saved, and the impact information (impact coordinates, impulse) was visualized. According to impulse, red was categorized as the point where a relatively large impulse occurred and purple as the point where the lowest impulse occurred. The calculated impact information was synthesized to create a tree risk map.

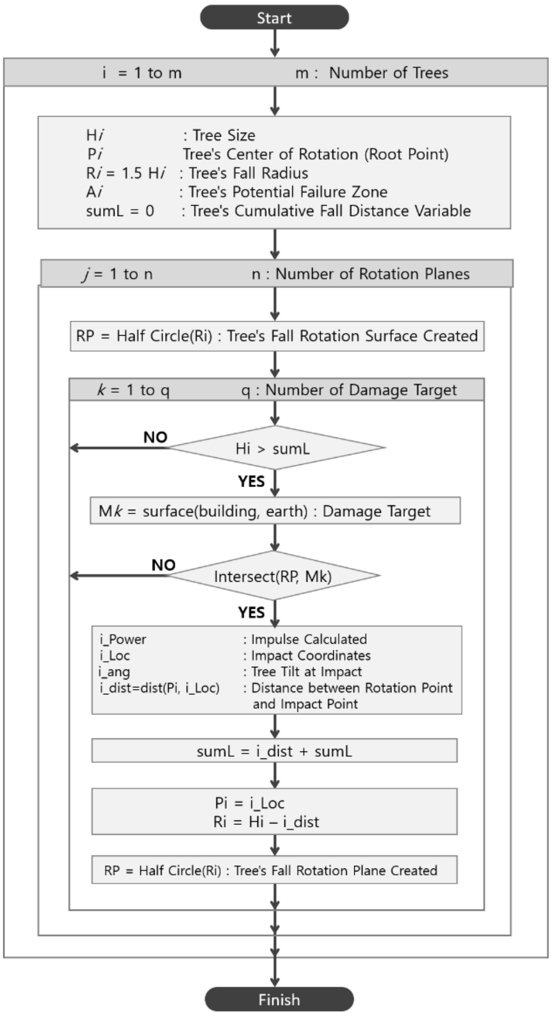


**Figure 4.** Process of calculating impulse

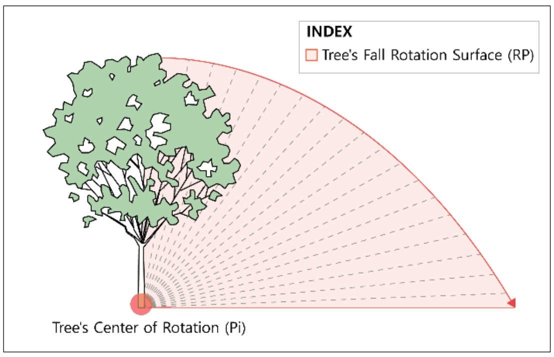


**Figure 5.** Creating a Fall Rotation Plane (RP)

### 3.3 Tree hazard mapping

This study examined the possibility of creating a tree risk map using the tree risk calculation algorithm. The target site was selected as a cultural property area that is subject to catastrophic damage to surrounding cultural properties and human life in the event of a tree falling. Yeongyeongdang and Aeryeonjeong of Changdeokgung Palace have various terrain elements and are adjacent to the viewing course. Many tall trees are growing around the pavilion and the pathway, which are expected to cause great damage to people and the surrounding pavilion in the event of a falling.

#### 3.3.1 Calculation of potential failure zone

This study calculated a potential failure zone for 211 trees over 10 meters tall growing in Yeongyeongdang and Aeryeonjeong of Changdeokgung Palace (Figure 6). The area of the calculated potential failure zone was divided into five grades with an equal interval of 20%. The red color indicates a tree with a large risk area, while the purple color indicates a tree with a small risk area. The number of Grade 1 trees was 30 weeks, and the number of trees with a risk area of more than 1000 ㎡ was 10 weeks. These trees mostly affected buildings and structures and areas with high foot traffic.

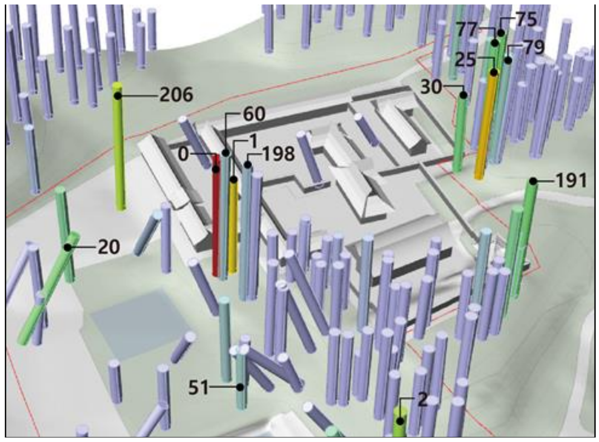


**Figure 6.** The calculation result of potential failure zone of Changdeokgung Palace Yeongyeongdang

#### 3.3.2 Calculation of Impulse

Trees with a large potential failure zone are more likely to cause damage to the surrounding area in the event of a hazard. Therefore, the calculation of the impulse was focused on trees with a potential failure zone of 1. The results of the impulse calculation were categorized into five grades, with the maximum and minimum values equally spaced by 20%. Points with relatively high impulse were visualized in red, and points with low impulse were visualized in purple. As a result of the impulse calculations, trees 206, 198, 199, and 60 generated a large impulse over 100kN·s.

The tree risk map was created by summarizing the results of the calculated impulses for each tree (Figure 7). When multiple impacts occurred at the same point, the largest impulse value was used as a representative value. By analyzing the created tree risk map, this study selected spaces with multiple predicted impacts and recorded impulses of Grades 1-2. This allowed us to objectively identify hazardous trees and areas that need prioritized management. As a result of analyzing the risk map, buildings with a high risk of a tree falling were identified as servants' quarters, Banbitgan, and Seonhyangjae. The spaces receiving the highest impulse were servants' quarters, Yeongyeongdang, and Seonhyangjae. Trees #206 and #198 were found to have a high impact on the front angle. In particular, tree 206 was distributed over a wide range of impacts due to its high height and narrow scope to prevent falling due to adjacent trees (Figure 8). It is predicted that the eaves of the servants' quarters will be subjected to high-intensity impacts, so continuous monitoring is required.

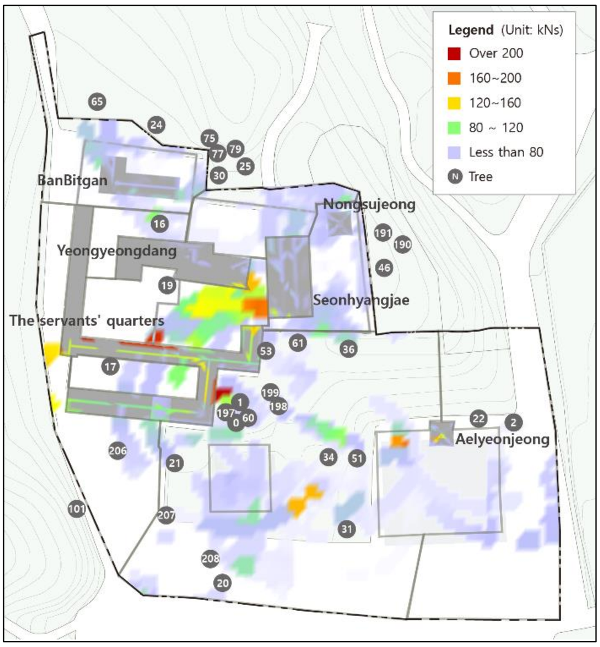


**Figure 7.** 3D Tree hazard map of Yeongyeongdang and Aeryeonjeong of Changdeokgung Palace

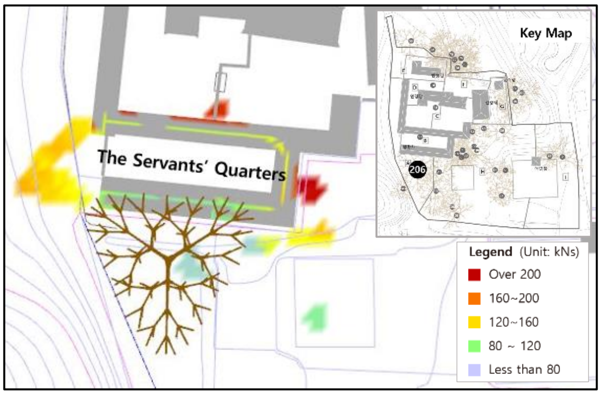


**Figure 8.** Tree impulse calculation result of No. 206

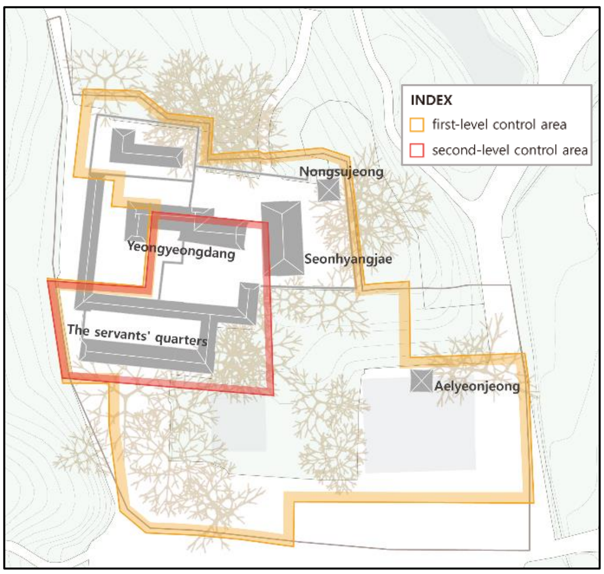


**Figure 9.** Example of setting up a management zone for weather conditions

Based on the tree risk map, this study set up areas that need to be controlled and prioritized in the event of a weather disaster (Figure 9). Areas with minor but possible risks were set as first-level control areas, and areas with high impulses were set as second-level control areas. Since the servants' quarters area is expected to have a large impulse when a tree falls, it should be set as a second-level control area to restrict access, and a response system should be in place to minimize damage. The non-hazardous areas should be used as viewing paths and evacuation routes.

## 4. CONCLUSIONS

The results of this study are as follows. First, the potential failure zone and impulse of a tree falling were established. The potential failure zone was calculated as a radius of 1.5 times the height. The range was 360° for upright trees and 180° for trees leaning to one side. For the impulse, this study calculated the angular momentum of the tree as it falls and converted it to linear momentum. Second, an algorithm was developed to calculate the risk of a tree falling. Rhino3D and Grasshopper were used to build the spatial information, and the derived formulas were used to code the functions of setting the initial value, calculating the risk, and retrieving the risk. The analysis results were mapped onto a three-dimensional model for visualization. Third, a tree risk map was created for Changdeokgung Palace. Through the tree risk map, this study identified spaces with high risk and high impact. Based on this, this study proposed areas that need to be controlled and managed.

The method proposed in this study is expected to be used to analyze the safety of surrounding cultural assets and visitors in the event of tree damage and to prevent disasters. However, there is a limitation that this study only considers tree trunk failure and does not calculate the risk of branches. Future research is required to improve its applicability in the field.

## ACKNOWLEDGEMENTS

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