Fragility Assessment of Vinyl Greenhouses and Livestock Sheds Subjected to Volcanic Ash Fall Hazards

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Abstract

In this study, fragility functions are developed to estimate expected volcanic ash damage to vinyl greenhouses and livestock sheds among common agricultural facilities in South Korea. The fragility functions are derived through the FOSM (first-order second-moment) analytical approach based on the thickness distribution of volcanic ash observed in the 1980 eruption of Mt. Saint Helens in the USA and on agricultural facility codes and specifications in South Korea. In this study, the volcanic ash fragility functions evaluated represent the conditional probability of failure of vinyl greenhouses and livestock sheds over the full range of volcanic ash loads. For the evaluation, 4 types (i.e., automated, single span, tree crop, and double span types) of multi-hazard resisting vinyl greenhouses and 3 types (i.e., standard, coastal, and mountain types) of livestock sheds conventionally utilized in South Korea are considered. All volcanic ash fragility functions estimated in this study are fitted using parameters of the lognormal CDF (cumulative distribution function), and the obtained parameters are compiled into a database for use in the future. The volcanic ash fragility functions developed in this study are intended to be used to evaluate potential risks and losses from volcanic eruptions around the Korean Peninsula.

Keywords: volcanic ash fragility; vinyl greenhouse; livestock shed; FOSM method; lognormal CDF

1. Introduction

Recently many large and powerful volcanic eruptions have been observed around the world. As an example, in August 2010, Mt. Sinabung on the northern part of the island of Sumatra in Indonesia erupted after more than 400 years of dormancy. Ash from this eruption was found as far as 5 km east of the crater of the volcano. Fifteen people died and thousands of residents living near its slopes were forced to evacuate the area. Many industries in the country suffered considerable damage as well (Iguchi et al., 2011).

Located at the north of the Korean Peninsula, Mt. Baekdu, an active volcano under which a magma chamber sits, last erupted in A.D. 946-947, shaping the mountain into its current form. It was one of the most violent volcanic eruptions of the past 2,000 years (Kim et al., 2013). If the mountain erupts again in the future, the related damage will be severe.

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(Received October 4, 2016; accepted March 6, 2018)
DOI http://doi.org/10.3130/jaabe.17.369

Table 1. Agriculture Related Facilities and Infrastructure

| Classification          | Type                                    |
|------------------------|-----------------------------------------|
| Agricultural Facility   | Vinyl Greenhouse, Livestock shed, Ginseng Greenhouse, Mushroom Greenhouse, Cold Storage Warehouse |
| Infrastructure          | Water Resources, Transportation, Communication, Power Supply |

In South Korea, vinyl greenhouses and livestock sheds surpass other agricultural facilities such as ginseng greenhouses, mushroom greenhouses, and cold storage warehouses in total gross area, as shown in Table 2. (MAFRA, 2005). Therefore, it is expected that these 2 types of facilities would contribute more to the total harm from deposition of volcanic ash compared to other types.

To estimate and mitigate potential losses from natural disasters, some countries are utilizing risk
assessment methods such as HAZUS®-MH (FEMA, 2010) and RiskScape (Kaye, 2007). Risk assessment requires modeling of both hazards and the fragilities of exposed elements (Ham et al., 2014). In South Korea, however, there has been a lack of studies on fragility assessment methodologies which would be able to identify risk subjected to volcanic ash fall hazards.

In this regard, this study assessed the volcanic ash fragilities of the frames of vinyl greenhouses and livestock sheds, which make up the largest share among agricultural facilities in South Korea, as shown in Table 2. Specifically, multi-hazard resisting vinyl greenhouses and livestock sheds as proposed by the Ministry of Agriculture, Food and Rural Affairs (MAFRA) were selected as assessment subjects (MAFRA 2008; MAFRA 2010). In addition, the first-order second-moment (FOSM) method was adopted to assess volcanic ash fragilities by comparing statistical values related to volcanic ash loads and facilities' load-resistance capacities. All of the volcanic ash fragilities assessed through the FOSM method were incorporated for further use into a database in the form of parameters of the lognormal cumulative distribution function (CDF). In the process, this study identified the volcanic ash fragilities for 8 types of multi-hazard resisting vinyl greenhouse and 3 types of livestock shed.

2. Methodologies for Assessing Volcanic Ash Fragility of Agricultural Facilities

This section provides methodologies for assessing the volcanic ash fragilities of agricultural facilities, agricultural facility models, and estimation methods to obtain volcanic ash loads and the load-resistance capacities of agricultural facilities.

2.1 Methodologies for Assessing Volcanic Ash Fragility

The volcanic ash fragility of agricultural facilities is a function representing the conditional probability of failure of an exposed facility due to loads generated by the deposition of volcanic ash. In general, there are 4 approaches to develop fragility functions related to natural disasters, as described in Table 3. (Schultz et al., 2010).

It is common for damage caused by natural disasters to be projected by analyzing reliable data from similar instances of damage. However, as there has been no reported damage caused by volcanic ash fall on the Korean Peninsula thus far, this study used an analytical approach to assess the volcanic ash fragilities of agricultural facilities.

### Table 2. Statistics on Agricultural Facilities in South Korea

| Classification           | Area   |
|--------------------------|--------|
| Vinyl Greenhouse         | 52,149 ha |
| Livestock Shed           | 358,000 EA |
| Ginseng Greenhouse       | 12,016 ha |
| Mushroom Greenhouse      | 1,246 ha |
| Cold Storage Warehouse   | 9,881 EA |

### Table 3. Fragility Modeling Approaches

| Approach     | Definition                                                                 |
|--------------|-----------------------------------------------------------------------------|
| Judgmental   | Fragility based on some form of expert opinion classified as judgmental.    |
| Empirical    | Empirical fragility is based on observational data documenting the performance of structures under a variety of loads. |
| Analytical   | Analytical fragility is based on analytical or numerical models that characterize the performance limit state of the structure. |
| Hybrid       | A hybrid approach for developing fragility uses a combination of two or more of the approaches described above in an attempt to supplement their various limitations. |

In general, fragility is expressed as either a vulnerability curve or a fragility curve. A vulnerability curve is the probability of mean damage occurring due to a random load, while a fragility curve provides the probability that a certain level of damage will be met or exceeded at a given random load. This study provides estimations of the probability of exceeding damage to agricultural facilities due to volcanic ash load to assess the fragility curve. The FOSM method was selected out of the analytical approach to assess volcanic ash fragilities, as shown in Table 4. (Schultz et al., 2010).

### Table 4. Analytical Fragility Modeling Methods

| Method  | Definition                                                                 |
|---------|----------------------------------------------------------------------------|
| FOSM    | - First-order second-moment  
|         | - Efficient and cost-effective method  
|         | - Based on well-known approximations                                        |
| FORM    | - First-order reliability method  
|         | - Extends first-order approximation method to handle non-normal basic random variables |
| SORM    | - Second-order reliability method  
|         | - Extends first-order approximation method to address nonlinear limit state equations |

FOSM-based fragility is obtained by first creating a limit state equation based on certain loads (Ekelen, 1997) and on the load-resistance capacities of structures, both assumed by a normal distribution function, and then estimating the probabilities of failure with the equation thus created. In this study, the limit state equation set based on volcanic ash loads and load-resistance capacities of agricultural facilities was implemented as follows:

\[ Z = R - V \]  

where \( Z \) denotes the safety margin of the agricultural facility against volcanic ash load, \( R \) is the load-resistance capacity of the agricultural facility, and \( V \) is volcanic ash load. In Eq. (1), \( Z > 0 \), \( Z = 0 \) and \( Z < 0 \) represents survival state, limit state, and failure state, respectively.

Fig.1 exemplifies a probability density function (PDF) of safety margin calculated based on the PDF of volcanic ash load and the agricultural facility's load-resistance capacity. The small portion shaded in black shown in the negative area indicates the probability of failure.
The reliability index of an agricultural facility against volcanic ash load can be calculated by dividing the mean of safety margin by standard deviation as expressed in the following Eq. (2):

\[
\beta = \frac{\mu_Z - \mu_V}{\sigma_Z + \sigma_V}
\]

where \(\beta\) denotes the reliability index of the agricultural facility against volcanic ash load, \(\mu_Z\) and \(\sigma_Z\) are the mean and standard deviation of the safety margin, respectively, \(\mu_V\) and \(\sigma_V\) are the mean and standard deviation of volcanic ash load, respectively.

The relationship between reliability index and probability of failure establishes the following Eq. (3) (Bensousan, 2005):

\[
P_f = 1 - \Phi(\beta) = \Phi(-\beta)
\]

where \(P_f\) denotes the probability of failure of the agricultural facility due to volcanic ash load and \(\Phi(\ )\) means the standard normal distribution function.

2.2 Facilities Subjected to Assessment of Volcanic Ash Fragility

This study developed volcanic ash fragilities for the 8 types of multi-hazard resisting vinyl greenhouse and 3 types of livestock shed as proposed by the MAFRA (2008; 2010).

The multi-hazard resisting vinyl greenhouses examined in this study are classified by the MAFRA (2010) into automated, single span, tree crop, and double span types, as shown in Table 5. In "07-Automated-01" of Table 5, "07" means the year in which MAFRA announced the vinyl greenhouse, and both "Automated" and "01" refer to a type of vinyl greenhouse. Each type of facility has a designated design snow depth.

Table 5. Type of Multi-Hazard Resisting Vinyl Greenhouse According to the Rural Development Administration of South Korea

| Structure Type       | Width (m) | Height (m) | Rafters, columns | Girders | Design snow depth (mm) |
|----------------------|-----------|------------|-------------------|---------|------------------------|
| **Automated Type**   |           |            |                   |         |                        |
| 07-Automated-01      | 7.00      | 4.70       | Rafters: Φ31.8×t1.5@60 Middles modeling of walls: Φ60×t2.1 | 9 EA (Φ25.4×t1.5) | 530                    |
|                      |           |            | Auxiliary rafters: Φ19.1×t1.2@100 Middles modeling of walls: - Upper cords: Φ60×t0.4@t2.3 - Diagonal members: round bar, Φ13 - Lower cords: Φ60×t2.3 | 7 EA (Φ48.1×t2.3) | 550                    |
| 10-Automated-01      | 8.00      | 7.40       | Rafters: Φ31.8×t1.5@60 Middles modeling of walls: Φ60×t2.1 | 9 EA (Φ25.4×t1.5) | 530                    |
|                      |           |            | Auxiliary rafters: Φ19.1×t1.2@100 Middles modeling of walls: - Upper cords: Φ60×t0.4@t2.3 - Diagonal members: round bar, Φ13 - Lower cords: Φ60×t2.3 | 7 EA (Φ48.1×t2.3) | 550                    |
| **Single Span Type** |           |            |                   |         |                        |
| 07-Single-01         | 5.00      | 2.60       | Rafters: Φ25.4×t1.5@60 | 7 EA (Φ25.4×t1.2) | 500                    |
| 10-Single-01         | 6.00      | 3.30       | Rafters: Φ31.8×t1.5@60 | 5 EA (Φ25.4×t1.5) | 410                    |
| **Tree Crop Type**   |           |            |                   |         |                        |
| 07-Tree-01           | 5.00      | 4.30       | Rafters: Φ31.8×t1.5@60 Columns: Φ48.1×t2.1@300 | 7 EA (Φ33.5×t2.1) | 400                    |
|                      |           |            | Auxiliary rafters: Φ25.4×t1.5@100 Columns: Φ31.8×t1.5@200 | 3 EA (Φ25.4×t1.2) | 440                    |
| 10-Tree-01           | 3.00      | 3.00       | Rafters: Φ25.4×t1.5@100 Columns: Φ31.8×t1.5@200 | 3 EA (Φ25.4×t1.2) | 440                    |
| **Double Span Type** |           |            |                   |         |                        |
| 10-Double-01         | 14.0      | 4.30       | Rafters: Φ33.5×t2.1@100 | 15 EA (Φ33.5×t2.1) | 330                    |
|                      |           |            | Middle modeling of walls: Φ48.1×t2.1@250 | 15 EA (Φ33.5×t2.1) | 330                    |
| 10-Double-02         | 16.0      | 4.50       | Hot dip galvanized truss @120 | 14 EA (Φ31.8×t1.7) | 350                    |

Table 6. Types and Dimensions of Livestock Sheds According to the National Agricultural Cooperative Federation of South Korea

| Classification       | Beef Barn | Dairy Barn | Pigsty | Hen House |
|----------------------|-----------|------------|--------|-----------|
| Available Number for Breeding | 275       | 140        | 1,613  | 2,543     |
| Building Area (m²)   | Min 624   | 586        | 245.38 | 453.6     |
|                      | Max 1,824 | 1,486      | 245.38 | 1,663.2    |
| Total Floor Area (m²) | Min 450   | 496.8      | 245.38 | 453.6     |
|                      | Max 1,650 | 1,324.8    | 245.38 | 1,663.2    |

| Type of Structure | Steel | Concrete | Steel |
|-------------------|-------|----------|-------|
| Eave Height (m)   | 5.0   | 3.6      | 3.2   |

*Fig.1. PDF of Safety Margin (V) – Facility Resistance (R)*

The reliability index of an agricultural facility against volcanic ash load can be calculated by dividing the mean of safety margin by standard deviation as expressed in the following Eq. (2):

\[
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| Type of Structure | Steel | Concrete | Steel |
|-------------------|-------|----------|-------|
| Eave Height (m)   | 5.0   | 3.6      | 3.2   |
Livestock sheds are divided into beef barns, dairy barns, pigsties, and hen houses according to kinds of livestock, as well as standard, coastal, and mountain types by the MAFRA (2008) in terms of regional location, as shown in Table 6. The structural design load for each facility is snow load. In Table 7., regional classifications of livestock sheds and region-specific basic ground snow loads, both provided by the specifications for livestock sheds as prepared by the MAFRA are outlined. This study assessed the structural load-resistance capacities of agricultural facilities based on design snow depths of multi-hazard resisting vinyl greenhouses and the design snow loads on roofs of livestock sheds in the corresponding areas.

### 2.3 Estimation of Volcanic Ash Load and Load-Resistance Capacity of Agricultural Facilities

The density of volcanic ash is about 10 times greater than that of snow load, as shown in Table 8. (Johnston, 1997).

Table 8. Densities of Snow and Volcanic Ash

| Classification       | Density (kg/m²) | Ratio of Volcanic Ash/Snow |
|----------------------|-----------------|-----------------------------|
| Damp Snow            | 100-200         |                             |
| Wet Volcanic Ash     | 1,000-2,000     | 10                          |

Johnston (1997) approximated load generated by the deposition of volcanic ash as in Eq. (4):

\[
L_v = \frac{dpg}{1000} \tag{4}
\]

where \(L_v\) denotes volcanic ash load (kPa), \(d\) means volcanic ash deposition (m), \(p\) is density of volcanic ash, and \(g\) is the acceleration of gravity (9.81 m/s²).

Table 8. and Eq. (4) suggest that volcanic ash loads can have a great impact on facilities. In South Korea, however, volcanic ash load is not taken into account in facility design.

This study identified the coefficient of variation (COV) of volcanic ash load and the mean and COV of the relevant facility’s load-resistance capacity in order to assess the volcanic ash fragility of agricultural facilities based on the FOSM method described in section 2.1. To identify the values, the literature on volcanic ash deposition was examined and estimation methods for the design load of the relevant facilities were used based on snow load provisions.

With regard to the volcanic ash loads, as volcanic ash flows through the air and falls to the earth’s surface by gravity, the distance that the volcanic ash floats and travels has a significant impact on the thickness of volcanic ash fall on the ground. Therefore, it is necessary to calculate the thickness of volcanic ash fall, taking into account the distance from the volcano where the ash originates to the area where the vinyl greenhouses and livestock sheds to be assessed are located. To properly reflect the variability of the thickness of volcanic ash deposition as a function of the distance from the volcano, this study used the means and standard deviations of volcanic ash deposition thicknesses observed in a study conducted by Nimlos (1982). The COV of volcanic ash fall used in this study was calculated based on the data measured in Montana, USA when Mt. Saint Helens erupted in 1980. Table 9. shows the means and standard deviations for the six sections: 0-15 km, 20-50 km, 55-85 km, 90-160 km, 165-215 km, and 220-365 km.

Table 9. Statistical Values of Volcanic Ash Fall Observed in the 1980 Eruption of Mt. Saint Helens in the USA

| Distance (km) | Mean (mm) | Standard Deviation (mm) | COV       |
|--------------|-----------|-------------------------|-----------|
| 0 - 15       | 250       | 110                     | 0.44      |
| 20 - 50      | 300       | 130                     | 0.43      |
| 55 - 85      | 340       | 140                     | 0.41      |
| 90 - 160     | 270       | 90                      | 0.33      |
| 165 - 215    | 220       | 70                      | 0.32      |
| 220 - 365    | 220       | 80                      | 0.36      |

This study used the statistical values (i.e., mean and standard deviation) for the six sections to reflect the variability of volcanic ash loads. Given the distance (600 km) from Mt. Baekdu to the center of the inside area of South Korea as illustrated in Fig.2., this study set the COV of the volcanic ash load at 0.32 as shown in Fig.3. by applying regression analysis as a power function.

![Fig.2. Distance (600 km) from Mt. Baekdu to Center of Inside in South Korea](image)

According to research conducted by Barnard (2010), a roof designed by the allowable stress design method is destroyed by volcanic ash loads that are 1.8-2.3 times greater than the design load as shown in Table 10.
Based on the results of Barnard's research (2010), the relationship between the mean of the load-resistance capacity (i.e., collapse) of the roof of the agricultural facility and the design load can be formulated as in Eq. (5):

\[ \mu_R = D_{L\alpha} \cdot C_f \]  

(5)

where \( \mu_R \) is the mean of the load-resistance capacity of the roof of the agricultural facility, \( D_{L\alpha} \) is design load determined by the allowable stress design method, and \( C_f \) is the failure coefficient, which is the ratio of the mean of the load-resistance capacity to design load.

If dead load and snow load are considered as gravity loads of the roof, the roof design load can be expressed as Eq. (6):

\[ D_{L\alpha} = D_d + S_s \]  

(6)

where \( D_d \) and \( S_s \) are respectively the dead load and snow load of the roof by the allowable stress design method.

This study used the design snow depth and ground snow load prescribed in the specifications of multi-hazard resisting vinyl greenhouses and livestock sheds as described by the MAFRA to estimate snow load, one of the major design loads on the roofs of agricultural facilities (as shown in Figs.4. and 5.) in South Korea.

The specifications of multi-hazard resisting vinyl greenhouses provide design snow depths as in Table 5. Therefore, nominal failure strength against volcanic ash loads can be obtained through Eq. (5) and (6). The specifications of livestock sheds provide not only ground snow load, but other factors that must be taken into account, including the ground snow load, exposure, thermal, importance, and slope factors in order to estimate design snow load applied to livestock sheds. The sloped roof snow loads based on the allowable stress design method of the Korean Building Code-Structural (KBC) (Architectural Institute of Korea, 2015) estimated as follows:

\[ S_\alpha = (C_b \cdot C_e \cdot C_t \cdot I_s \cdot S_g) \cdot C_s \]  

(7)

where \( C_b \) denotes the basic roof snow load factor, \( C_e \) is the thermal factor, \( I_s \) is the exposure factor, \( S_g \) is the basic ground snow load, and \( C_s \) is the slope factor.

In the KBC, values of exposure, thermal, importance and slope factors described in Eq. (7) can be obtained from Tables 11. through 13. and Fig.6.
In this study, the basic roof snow load factor was fixed at 0.7 as suggested in the KBC. The exposure factor was assigned as 1.0 while assuming that there were no sheltering effects occurring by terrain, nearby facilities, and other structures. The thermal factor and importance factor were set at 1.2 and 0.8, respectively, because the livestock sheds in question are unheated structures and fall into risk category III. The basic ground snow load was set as suggested in Table 7. The slope factor was fixed at 0.94, the value applied when a roof has no obstacles, its surface is smooth, and its slope is 18.4°.

The variability of failure load varies depending on the type of members installed in the facility in question and the mode of failure. Considering that the roof framework of multi-hazard resisting vinyl greenhouses and livestock sheds is mostly structural steel and using data from preceding studies (NEMA, 2009), this study set the COV at 0.10. Standard deviation of load-resistance capacity was obtained by multiplying the COV (0.10) by the mean of the load-resistance capacity of the roof of an agricultural facility.

### 2.4 Measures to Build a Volcanic Ash Fragility Database

In this study, the assessed volcanic ash fragilities of agricultural facilities were entered into a database in the form of parameters of lognormal CDF. Lognormal CDF is expressed as follows (Straub and Kiureghian, 2008):

$$F_r(x) = \Phi\left[\frac{\ln(x) - m_R}{\xi_R}\right]$$

where \(\Phi[\ ]\) refers to standard normal distribution function, \(x\) indicates volcanic ash deposition, \(m_R\) is median capacity which is dimensionally consistent with demand \(x\), and \(\xi_R\) is standard deviation of \(\ln(x)\).

As an optimization method for parameters of lognormal CDF, the least squares method as expressed in Eq. (9) was used (Baker, 2015).

$$\bar{m}_R, \bar{\xi}_R = \min \sum_{v=1}^{m} [P_f(x) - F_r(x)]^2$$

In this equation, \(P_f(x)\) represents the probability of failure of agricultural facilities, calculated by the FOSM method, and \(F_r(x)\) indicates the volcanic ash fragility of agricultural facilities, optimized by the least squares method.

### 3. Assessment of Volcanic Ash Fragility and Database Construction Results

This section describes the volcanic ash fragilities of multi-hazard resisting vinyl greenhouses and livestock sheds assessed on the basis of the FOSM method, along with the results of the related database construction.

#### 3.1 Volcanic Ash Fragility of Multi-hazard Resisting Vinyl Greenhouse

Table 14 lists parameters of the lognormal CDF for volcanic ash fragilities of automated, single span, tree crop, and double span vinyl greenhouses. The parameters of the lognormal CDF were optimized as shown in Eq. (9). Fig. 7 shows the fragilities of 4 different types of multi-hazard resisting vinyl greenhouses, divided based on use (i.e., 10-Automated-01, 10-Single-01, 10-Grape-01, and 10-Double-01) according to volcanic ash deposition. Figs. 8 through 11 illustrate the fragilities of automated vinyl greenhouses (i.e., 07-Automated-01 and 10-Automated-01), single span vinyl greenhouse (i.e., 07-Single-01 and 10-Single-01), tree crop vinyl greenhouse (i.e., 07-Grape-01 and 10-Grape-01), and double span vinyl greenhouse (i.e., 10-Double-01 and 10-Double-02), respectively.

![Fig.6. Roof Slope Factors for Warm and Cold Roofs](image)

Fig. 6 illustrates the volcanic ash fragility of 4 types of multi-hazard resisting vinyl greenhouses with different uses (i.e., 10-Automated-01, 10-Single-01, 10-Grape-01, and 10-Double-01). In this figure, a dramatic change in the probability of failure is observed when volcanic ash deposition is between 40 mm and 250 mm. When the volcanic ash deposition is 100 mm, the probabilities of failure of 10-Automated-01, 10-Single-01, 10-Grape-01, and 10-Double-01 are approximately 37%, 68%, 61%, and 86%, respectively. The differences in the probability of failure are deemed to be attributable to different sectional properties of members and frameworks in vinyl greenhouses, along with different load-resistance capacity due to the differences in design snow depth as
In the volcanic ash fragility of automated vinyl greenhouses (i.e., 07-Automated-01 and 10-Automated-01) shown in Fig.8., the probability of failure drastically increases between a volcanic ash deposition of 40 mm and 200 mm. When the volcanic ash deposition reaches 100 mm, the probability of failure of 07-Automated-01 is approximately 41%, while that of 10-Automated-01 is about 37%. It can be inferred that the difference in the probability of failure of the 2 automated vinyl greenhouses is attributable to different sectional properties of the framework, such as the rafters and columns. In 07-Automated-01, the only middle modeling of walls of Φ48.1×t2.1×@300 was used, while the middle modeling of walls used in 10-Automated-01 included upper cords of Φ60×40×t2.3, diagonal members of round bar and Φ13, and lower cords of Φ60×40×t2.3.

In the volcanic ash fragility of single span vinyl greenhouses (i.e., 07-Single-01 and 10-Single-01) shown in Fig.9., the probability of failure increases substantially when the volcanic ash deposition is between 40 mm and 200 mm. When the volcanic ash deposition reaches 100 mm, the probability of failure of 07-Single-01 is about 47%, and that of 10-Single-01 is about 68%. It can be inferred that the probability of failure of the 2 single span vinyl greenhouses differs not because of the differences in section properties shown in Table 5., but because of the difference in the specifications (i.e., width and height.)

In the volcanic ash fragility of tree crop vinyl greenhouses (i.e., 07-Grape-01 and 10-Grape-01) shown in Fig.10., the probability of failure increases significantly when the volcanic ash deposition is between 40 mm and 200 mm. When the volcanic ash deposition reaches 100 mm, the probability of failure of 07-Grape-01 is about 71%, and that of 10-Grape-01 is about 61%. The difference in the probability of failure between the 2 types of tree crop vinyl greenhouses is attributable to different sectional properties of the framework, such as the rafters and columns. In 07-Grape-01, rafters of Φ31.8×t1.5×@60 and columns of Φ48.1×t2.1×@300 were used, while rafters of Φ25.41×t1.5×@100 and columns of Φ31.8×t1.5×@200 were used in 10-Grape-01.

In the volcanic ash fragility of double span vinyl greenhouses (i.e., 10-Double-01 and 10-Double-02) shown in Fig.11., the probability of failure dramatically changes when the volcanic ash deposition is between 30 mm and 150 mm. When it reaches 100 mm, the probabilities of failure of 10-Double-01 and 10-Double-02 are roughly 86% and 82%, respectively. The volcanic ash fragility of the 2 double span vinyl greenhouses was assessed as almost the same because the design snow depth suggested in the specifications of multi-hazard resisting vinyl greenhouses, listed in Table 5., were only slightly different (20 mm).

3.2 Volcanic Ash Fragility of Livestock Sheds

Fig.12. and Table 14. describe the volcanic ash fragilities for standard-type, coastal-type, and mountain-type livestock sheds and the parameters

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**Table 5.**

| Type            | Design Snow Depth (mm) | Rafter Material | Column Material |
|-----------------|------------------------|-----------------|-----------------|
| Mountain-Type   | 150                    | Φ31.8×t1.5×@60  | Φ25.41×t1.5×@100 |
| Coastal-Type    | 150                    | Φ31.8×t1.5×@60  | Φ25.41×t1.5×@100 |
| Standard-Type   | 150                    | Φ31.8×t1.5×@60  | Φ25.41×t1.5×@100 |

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**Fig.7.** Volcanic Ash Fragilities for Four Types of Multi-hazard Resisting Vinyl Greenhouses

**Fig.8.** Volcanic Ash Fragilities of Automated Vinyl Greenhouses

**Fig.9.** Volcanic Ash Fragilities of Single Span Vinyl Greenhouses

**Fig.10.** Volcanic Ash Fragilities of Tree Crop Vinyl Greenhouses

**Fig.11.** Volcanic Ash Fragilities of Double Span Vinyl Greenhouses

**Fig.12.** Volcanic Ash Fragilities for Three Types of Livestock Sheds

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JAABE vol.17 no.2 May 2018  Hee Jung Ham  375
of relevant lognormal CDF according to arbitrary volcanic ash depositions, respectively.

| Structure Type | $m_m$ | $\xi$ |
|----------------|-------|-------|
| Standard Type  | 5.026 | 0.368 |
| Coastal Type   | 5.222 | 0.368 |
| Mountain Type  | 6.057 | 0.364 |

In Fig.12., the volcanic ash fragility curve of mountain livestock sheds is greatly different from those of standard and coastal livestock sheds. With the volcanic ash fragility of the latter 2 types of livestock sheds, the probability of failure substantially increases when volcanic ash deposition is between 60 mm and 500 mm, while that of mountain livestock sheds increases when volcanic ash deposition is between 160 mm and 1,000 mm. It is confirmed that when volcanic ash deposition is 200 mm, the probabilities of failure of standard livestock sheds and coastal livestock sheds are roughly 77% and 58%, respectively, while that of mountain livestock sheds is about 2%. These figures suggest that because their design strength is high enough to resist snow loads, mountain livestock sheds are safer structures against volcanic ash loads compared to the other 2 types.

4. Conclusions

In this study, fragilities against volcanic ash deposition were assessed using as study subjects the frameworks of multi-hazard resisting vinyl greenhouses (i.e., automated, single span, tree crop, and double span types) and livestock sheds (i.e., standard, coast, and mountain types).

In order to assess volcanic ash fragilities, statistics on volcanic ash load and the load-resistance capacity of agricultural facilities were identified from the available literature and specifications and probabilities of failure were estimated on the basis of a reliability index by using the FOSM method. In addition, to establish a database of volcanic ash fragilities as assessed by the FOSM method, the fragilities were optimized in the form of parameters of the lognormal CDF using the least squares method.

This study discovered that when the same amount of volcanic ash is deposited, the fragilities of automated, single span, tree crop, and double span vinyl greenhouses vary depending on their specifications, as well as on their sectional and material properties. In the assessment of volcanic ash fragility of livestock sheds, it is confirmed that mountain livestock sheds provide a safer structure against volcanic ash load compared to standard and coastal livestock sheds.

It is inferred that the volcanic ash fragilities assessed in this study can be further used for risk assessment of agricultural facilities with regard to volcanic ash in events of volcanic eruptions around the Korean Peninsula. As regards future research, validation of developed fragility curves will be necessary with post-disaster surveys on the damage of agricultural facilities caused by snow or volcanic ash fall hazards.

Acknowledgement

This research was supported by a grant [MOIS-DP-2015-07] through the Disaster and Safety Management Institute funded by Ministry of the Interior and Safety of Korean government.

References

1) Architectural Institute of Korea (2015) Korean building code-structural, Kimoondang, Ministry of Land, Transport and Maritime Affairs, p.772.
2) Baker, J.W. (2015) Efficient analytical fragility function fitting using dynamic structural analysis, Earthquake Spectra, Vol. 31(1), pp.579-600.
3) Barnard, S.T. (2010) The vulnerability of New Zealand lifelines infrastructure to ashfall, Ph.D. dissertation, Department of Geological Sciences, University of Canterbury, p.286.
4) Bensoussan, A. (2005) Reliability index, Advances in Computational Management Science, Vol. 7(1), pp.311-317.
5) Donga Studio (2015) Ash Deposition Can be Reached up to 10 cm by Baekdu Mountain Volcano Eruption, http://studio.donga.com /View?idxno=201505210027&c=00030003
6) Ekelen, A.J. (1997) Review and selection methods for structural reliability analysis, Delft University Press, p.44.
7) FEMA (2010) Multi-hazard loss estimation methodology hurricane model, Technical Manual: Department of Homeland Security, Washington, D.C., p.552.
8) Ham, H.J., Yun, W.S., Kim, H.J. and Lee, S. (2014) Evaluation of extreme wind fragility for balcony windows installed in mid/low-rise apartments, Journal of Korean Society of Hazard Mitigation, Vol. 14(1), pp.19-26.
9) Iguchi, M., Ishihara, K., Surono and Hendrasto, M. (2011) Learn from 2010 eruptions at Merapi and Sinabung volcanoes in Indonesia, Disaster Prevention Research Institute Kyoto University, No. 54B, pp.186-194.
10) Johnston, D (1997) Physical and social impacts of past and future volcanic eruptions in New Zealand, Ph.D. dissertation, Massey University, p.288.
11) Kaye, G.D. (2007) RiskScape volcano – a volcanic hazard risk assessment model for RiskScape, GNS Science Report 2007/38, p.176.
12) Kim, S.W., Choi, E.K., Jung, S.J., Kim, S.H., Lee, K.H. and Yun, S.H. (2013) A preliminary study for predicting a damage range of pyroclastic flows, lahars, and volcanic flood caused by Mt. Baekduan eruption, Korean Earth Science Society, Vol. 34(6), pp.479-491.
13) MAFRA (2005) Agroforestry major statistics, Ministry of Agriculture, Food and Rural Affairs, p.493.
14) MAFRA (2008) Standard design of the livestock shed, National Agricultural Cooperative Federation, p.232.
15) MAFRA (2010) Standard plans and specifications of horticultural & herbal facilities, Rural Development Administration, p.478.
16) NEMA (2009) Development of the assessment technique to wind and snowfall hazard. Natural Hazard Mitigation Research Group, National Emergency Management Agency, p.279.
17) Nimlos, T.J. and Hans, Z. (1982) The distribution and thickness of volcanic ash in Montana, Northwest Science, Vol. 56(3), pp.190-198.
18) Schultz, M.T., Gouldby, B.P., Simm, J.D. and Wibowo, J.L. (2010) Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability, US Army Corps of Engineers, p.50.
19) Straub, D. and Kiureghian, A. (2008) Improved seismic fragility modeling from empirical data, Structural Safety, Vol. 30(4), pp.320-336.