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journal homepage: www.elsevier.com/locate/issn/15375110

Research paper

Evaluation of wind pressure coefficients of single-span greenhouses built on reclaimed coastal land using a large-sized wind tunnel

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ARTICLE INFO

Article history:
Received 29 May 2015
Received in revised form
15 October 2015
Accepted 16 November 2015
Published online 17 December 2015

Keywords:
Greenhouse
Reclaimed land
Single-span
Wind pressure coefficient
Wind tunnel

The government of Korea has announced a plan to develop large-scale greenhouse complexes on reclaimed coastal land. Wind characteristics over coastal regions are different from those of inland because of topographical and meteorological characteristics. A greenhouse facility is classified as a light-weight structure that is vulnerable to heavy wind loads. Reference to the newly modified greenhouse design standards, particularly for the reclaimed lands, has been required to ensure structural safety in strong winds. To evaluate the structural safety of greenhouses according to the wind characteristics for coastal reclaimed lands, the wind environments of these regions were simulated in a large scale Eiffel type wind tunnel. Variations in the windward terrain roughness were computed using the wind and turbulence intensity profiles based on ESDU (Engineering Sciences Data Unit, E01008) code. The wind pressure coefficients of four typical single-span greenhouses used in Korea, (Even-span, Three-quarter, Peach and Mono-span) were measured in the wind tunnel according to wind direction, roof slope and the radius of curvature of the roof. The wind pressure coefficients of the 4 types of greenhouses were proposed in terms of their structural design and cladding. The proposed wind pressure coefficients values will be valuable for greenhouse designers and manufacturers.

1. Introduction

Vegetable consumption in South Korea has been steadily increasing. It has risen from 59.9 kg per capita in 1970 to 170 kg in 2013 (Statistics Korea, 2014). To fulfil the increasing demand for high quality vegetable production, more horticulture facilities are required.

The cultivation area of the horticulture facilities in South Korea was 52,530 ha in 2012 (Ministry of Agriculture, Food and Rural Affairs of Korea, 2014) but Government recently

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http://dx.doi.org/10.1016/j.biosystemseng.2015.11.007
1537-5110/

Nomenclature

C_p	Average wind pressure coefficient (dimensionless)
E_L	End-wall-leeward part
E_S	End-side part
E_W	End-wall-windward part
K	Wind speed profile factor (dimensionless)
P	Pressure difference (Pa)
p_P	Static pressure at an arbitrary point (Pa)
p_∞	Static pressure at windward regions (Pa)
q_H	Dynamic pressure measured at average roof height of greenhouse (Pa)
R_L	Roof-leeward part
R_S	Roof-side part
R_W	Roof-windward part
W_L	Wall-leeward part
W_S	Wall-side part
W_W	Wall-windward part
α	Roof slope (°)

announced a development plan for a large-scale greenhouse complex to harvest higher value-added vegetables: 5185 ha of high-tech horticulture facilities on 12 reclaimed coastal lands to provide produce for both the domestic and overseas markets (Ministry of Agriculture, Food and Rural Affairs, 2014). However, wind environments over these coastal lands are entirely different from those of the inland area due to their relatively mild surface roughness and the behaviour of turbulent convection. The return period for strong winds or huge typhoons has been recently shortened due to changes in the global climate, especially in the western coastal regions of the country where the bulk of the reclaimed land is located (Korea Meteorological Administration, 2014). Economic loss due to the destruction of greenhouses by strong winds is a critical problem for the horticulture industry. Greenhouse facilities are classified as light-weight structures and they are highly vulnerable to heavy wind loads compared to general buildings. *Muifa*, the 9th typhoon of 2011, attacked the west coastal region of South Korea and destroyed 42.08 ha of agricultural facilities, resulting in approximately 4.1 million $ US in economic losses (Ministry of Public Safety and Security, 2012). As a result, new modified greenhouse design standards, especially for use in coastal regions, have been required to secure their structural safety in response to the strong winds environment. Therefore, a research priority in support of this expansion in production is the collection of preliminary data for wind pressure and wind pressure coefficients for the new designs.

Various field studies have been conducted to investigate the characteristics of the wind pressure acting on the agricultural facilities. Among these studies, Wells and Hoxey (1980) investigated the wind loads on 5 glass-covered greenhouses under natural wind conditions, and Hoxey and Richardson (1984) measured the wind loads on plastic film and arch-type greenhouses, which represented the commercial greenhouses used in the UK. Richardson (1993) also measured the distribution of the external and internal wind pressure coefficient of single-span plastic film livestock buildings to support a "European code of practice for the design of tunnel buildings." Field studies have traditionally been regarded as practical approaches giving most reliable data. By contrast, these approaches have shown various experimental limitations: 1) difficulties in acquiring data due to unstable and unpredictable external weather conditions; 2) difficulties in the simultaneous measurement of wind pressure on large surfaces of the structure with multiple measurement points; and 3) time- and labour-consuming problems. Thus, wind tunnels have been regarded as economic and accurate tools for conducting aerodynamic research. Various experimental studies have also been actively carried out to measure the indoor and outdoor environmental characteristics of the agricultural facilities, including ventilation, airflow pattern, and wind pressure, using the wind tunnel in the agricultural areas. Sase, Kozai, Nara, and Negishi (1980) conducted wind tunnel experiments to measure the wind pressure and discharge coefficients for a single-span greenhouse, and Sase, Takakura, and Nara (1984) also investigated the distribution of airflow and air temperature using a naturally ventilated small-scaled greenhouse model. Choiniere and Munroe (1994) studied the airflow pattern inside a naturally ventilated pig-rearing house using a model based on a commercial livestock building type in Canada. Lee et al. (2003) conducted a Particle image velocimetry test to examine the ventilation and turbulence characteristics of a fully open-roof and Venlo-type multi-span greenhouse. De Paepe et al. (2013) recently measured the air velocities in and around a 1:60 scale models of a dairy cattle house to investigate the effect of the wind incidence angle. In the case of wind load-related studies, Yang, Li, Xue, and Huang (2013) studied two main areas: the variation of wind loadings with wind direction on a single-span plastic film greenhouse, and the critical wind velocity required to impair an experimental solar greenhouse. Tecle, Bitsuamlak, and Jiru (2013) studied natural ventilation for a low-rise building according to the size of the openings and the combination of the opening shape using a boundary-layer wind tunnel. Qiu, Sun, Wu, and Tamura (2014) investigated the influence of Reynolds number on the mean wind loads acting on cylindrical roofs with different aspect ratios; the experimental-scaled models did not simulate an agricultural facility although the physical appearance of the model was very similar to that of the Arch type greenhouse.

In this study, the object was to establish newly modified greenhouse design standards, especially for the facilities that were built on coastal reclaimed lands. Firstly, the wind environments of the target regions were simulated in the wind tunnel using ESDU (Engineering Sciences Data Unit, E01008) code. Variations in the upwind terrain roughness of the target regions were considered to accurately simulate the wind and turbulence intensity profiles. Then, the wind pressure coefficients of a commercial single-span greenhouse facilities, such as Even-span, Three-quarter, Peach and Mono-span types, were measured according to wind direction and design factors, such as the roof inclination and the radius of the curvature of the roof materials. Measured wind pressure coefficient data according to the each environmental condition were analysed in terms of the structural design and