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# WIND-INDUCED PRESSURE FOR SILSOE CUBE TESTED IN THE WIND-INDUCED DAMAGE SIMULATOR

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**Abstract:** A new wind testing facility, the Wind-induced Damage Simulator (WDS), was designed and built at the University of Ottawa. The new facility is capable of generating extreme wind conditions and can achieve high pressure testing environment for scaled models as well as for full-scale structural elements such as: roofs, windows and curtain walls. The WDS system has dimensions of 3.65 m x 3.65 m x 3.0 m and has 20 circular inlet openings on the four lateral walls. The outlet of the box has a diameter of 300 mm, is at the center of the roof and it is connecting to a powerful industrial blower through a steel duct. Scaled models, 1:30 and 1:40 of the Silsoe cube, which is a basic shape structure was and a total of 42 pressure taps were installed on its surface. Pressure measurements were performed for unidirectional and shear wind flow conditions determined by activating the first and second inlets at the corner of the WDS. Also, different positions of the Silsoe cube model were investigated for determining the optimum testing section for the WDS. Results comparison with pressure distribution reported for the full-scale Silsoe cube showed that for certain arrangements the WDS induced pressure was similar with the full-scale measurements.

Key words: Wind-induced pressure, Silsoe cube, Wind-induced damage simulator

## 1 INTRODUCTION

Wind, as one of the most common phenomena on earth, is caused by the differences of pressure in the atmosphere. Structures exposed to wind effects are also affected by the wind-induced pressure. Based on the nominal area of the structure, the force induced by the pressure differences applied on the structure can be estimated. The magnitude of the wind speed can vary significantly based on the geographical region reaching highest value when wind-induced hazards such as hurricanes and tornados are reported. Since there are large fluctuation in the wind intensity, the wind effects can't be ignored in the current structural design.

To study the wind effects on structures, relevant facilities, computerized models, or mathematical models have been established to simulate the natural wind conditions. Tornados, hurricanes, downburst, wind shear and gust wind are common wind hazards as potentially, they have the ability to cause damage or negative impacts for structures. The wind speed of a tornado can vary from less than 180 km/h to more than 480 km/h and the range of its travel distance could be from 3 km to over 100 km. (Fujita 1971). According to the Saffir Simpson Hurricane Wind Scale (The Saffir-Simpson Team 2012), the hurricane can be classified into 5 categories. Category one to three, the wind velocity varies from 33 m/s to 58 m/s. The wind velocity for hurricanes of categories four and five varies from 58 m/s to more than≥ 70 m/s. The corresponding dynamic pressure could increase up to 3 kPa or more. A wind testing facility is able to duplicate one or multiple wind hazard damaging mechanisms and it usually consists of one or a series of fans to move the air and create airflow; a tunnel or an enclosure made out of solid materials to contain the testing object and designed to resist the wind effects produced by the fan; auxiliary installations to enhance the airflow performance; observation equipment and sensors to monitor velocity and air pressure; etc. Differences between various wind testing facilities are mostly due to the differences in the wind flows they can replicate. Conventional wind tunnels usually generate turbulent and laminar-flows and assume that the wind always comes from one direction. Meanwhile, by rotating the entire model, measurements for all wind directions can be recorded. To simulate the testing object's surrounding environment and to produce turbulence, a certain magnitude of roughness length and other structure models around the testing object need to be set up in the wind tunnel. Moreover, nowadays, computational fluid dynamics software is more and more used to predict and visualize the wind effects on testing objects. Both the wind tunnel simulator and the CFD simulator are usually used to improve the accuracy and reliability of the tests.

## 2 Wind-induced Damage Simulator

The Wind-induced Damaged Simulators (WDS) was designed and built at the University of Ottawa to replicate different kinds of wind engineering testing experiments, the entire system includes a 3.6 m x 3.6 m x 3.0 m steel box (Figure.1) of a quarter inch thickness and with a web of HSS elements of various sections, which are able to resist up to 30 kPa uniform pressure applied to the box surface to ensure the safety and stability of the experimental chamber during the experiments. Five windows are distributed on the four lateral walls for observation purpose. Five circular openings with a diameter of 150 mm were designed on each lateral wall of the WDS and they are at the same location on the lateral wall. Four of the openings on each wall are aligned 350 mm above the ground with the same spacing of 915 mm between them and the side ones are located at 460 mm from the vertical edge of the wall. The remaining circular opening is right above the rightmost aligned openings but at 700 mm above ground. Different shapes of inlet modules can be installed at the circular opening to control the inclination angle of the box inflow. Each module consists of a steel duct and a steel plate and can be easily removed and installed manually. Steel plates with gaskets are also manufactured for the situations that the opening needs to be closed. A circular outlet with a diameter of 300 mm is located at the center of the roof of the wind box and it is connecting to a powerful industrial blower through a steel duct. Between, a filter is placed to prevent any debris of the tests from entering and damaging the blower. The blower is sucking air out of the box and generates a vacuum environment inside the box. It is able to provide up to 40 m/s flow at the outlet of the box as well as produce and keep up to 14 kPa vacuum pressure in the wind box. With only one inlet open, 90m/s ejection flow can be obtained at the inlet. For comparison, the wind speed of the recorded most devastating category 5 hurricane (Hurricane Allen 1980) in history went up to 85 m/s and the pressure difference between the center of the hurricane and the normal atmosphere was 13.5 kPa. Thus, the WDS is able to simulate most devastating wind scenarios in the world. To reduce the noise from the high velocity flow which comes out from the blower a silencer and a dissipater were installed at the outlet of the blower. The dissipater will ensure the maximum outflow velocity it lower than 20m/s when the blower is at its maximum capacity.

Different experimental setups can be designed and built inside the box to properly carry out the tests with diverse configuration. The examples presented in Figure 3 represents experimental setups which are shallow lateral walls or a large chamber above the testing sample, to create essential pressure conditions for the tests. In addition, the testing models can be installed on the floor of the wind box, which has threaded holes, allowing installations of fastening systems or any other accessories. Other apparatuses such as pressure scanners and velocity probes were used to take the necessary measurements. There are three functions expected from the WDS: the pressure induced damage test, tornado-like flow simulation, and the conventional boundary layer wind tunnel like test. In this article, a conventional-boundary-layer-wind-tunnel-like test will be discussed.

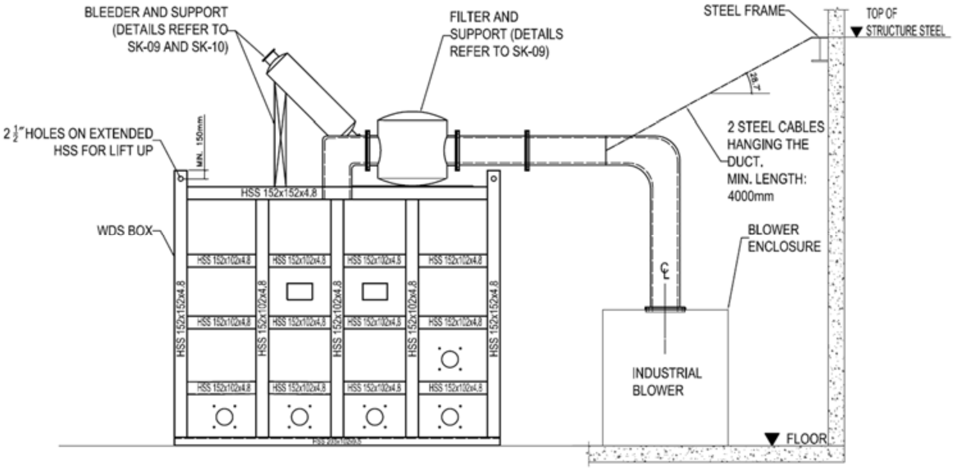

Figure 1: The Wind induced Damage Simulator (WDS) overall schematic

Figure 2: The Wind induced Damage Simulator (WDS)

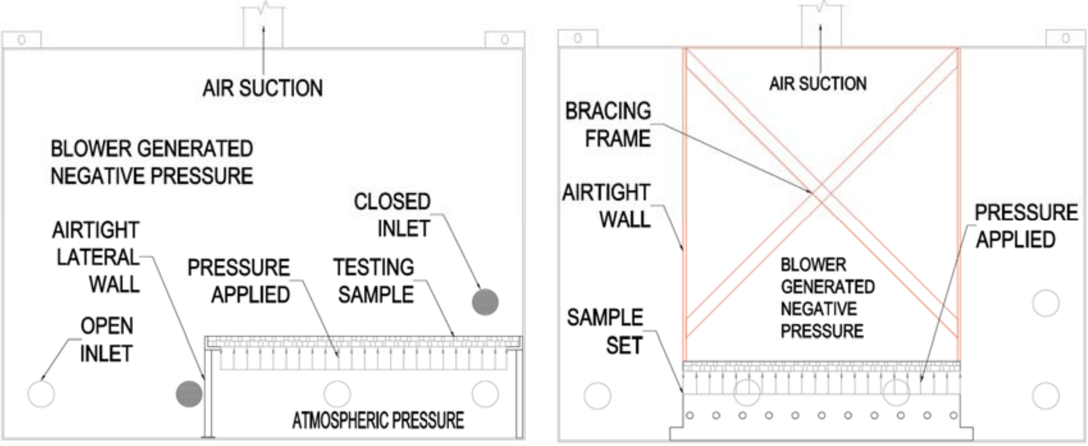

Figure 3: Experimental setup examples

The power source of the pressure and the flow in the WDS are all from the blower. The blower draws air out of the box through the steel duct connecting to the outlet of the WDS. As a result, the vacuum pressure was generated inside the WDS, which will drive flow at the inlet into the WDS box and produce an ejection flow. Theoretically, the pressure to the velocity scale follows the Bernoulli's equation (Fluid Mechanics 1973):

[1] $P_A - P_V = \frac{1}{2}\rho {V_V}^2 - \frac{1}{2}\rho {V_A}^2$

$P_A$ and $P_V$ refer to the atmospheric pressure and the vacuumed pressure inside the box respectively. Assume that the flow velocity $V_A$ outside the box equals to 0. Correspondingly, $V_V$ becomes the flow velocity at the inlet. The ρ represents the flow density. Knowing the pressure-velocity relationship, the flow velocity at the inlet can be derived during the test. Meanwhile, the pressure readings are controlled by changing the fan power as well as the amount of the opened inlets.

## 3 Silsoe Cube Model Validation

As the flow testing conditions in the WDS are different from the testing conditions in the conventional wind tunnels, a basic structure, the Silsoe Cube (Richards 2001), was used for reference as well as the validation of the flow tests in the wind box. The Silsoe Cube is a 6 m cubic structure designed and built at the Silsoe Research Institute. The purpose of instrumenting this cube was to investigate the interaction between the structure and the wind (Castro 1976). This cube was placed in an 'open country' environment which means that the cube is exposed to the natural atmospheric pressure and wind conditions. Pressure measurements were carried out at the centerline of each surface vertically and horizontally. Additional pressure measurements were also performed at the roof of the cube in the full-scale test. Wind velocity was recorded at the reference location near the cube and was transformed into the dynamic pressure. Thus, the pressure coefficient could be derived from the mean surface pressure and the dynamic pressure.

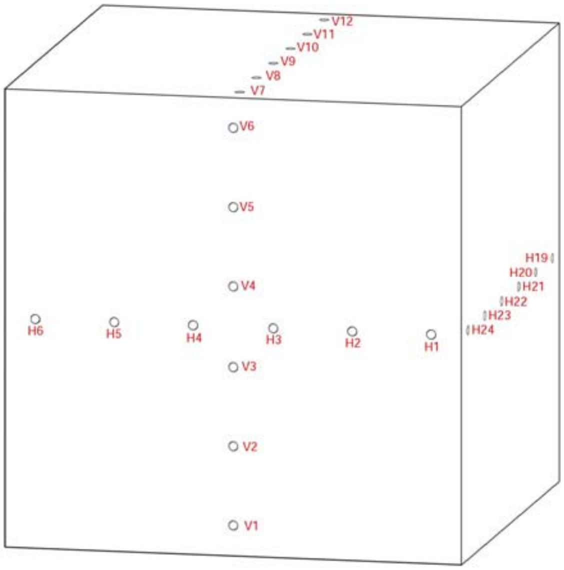

Figure 4: Silsoe Cube and pressure measurement locations

### 3.1 Scaled Silsoe Cube Tests

Considering the circular opening size on the WDS, 1:40 and 1:30 scaled Silsoe Cube models were tested in the experiment. An artificial floor made of plywood with supporting legs was initially installed in the WDS. The artificial floor was designed to be flush with the bottom of the circular opening as well as to have enough space underneath for measuring devices. Circular openings were cut on the artificial floor at designated locations to let vinyl tubes have access from the Silsoe Cube model to the pressure scanners under the artificial floor. The scaled Silsoe Cube model was installed at the circular opening with fixing components. So that it would remain stable even under the high velocity flow testing condition.

As shown in Figure 5, coordinate A1, A2, B1 and B2 are the four chosen locations to place the scaled model. Gridline A is 305mm and parallel to the south wall of the WDS and at the center of an inlets on the west wall. Gridline B is also at the centerline of an inlet on the west wall and is 1.13 m and parallel to the gridline A.  Gridline C and D are symmetrical to gridline A and B. As the WDS is a square from the top view, gridline 1, 2, 3 and 4 are the same relationship as gridline A, B, C and D.

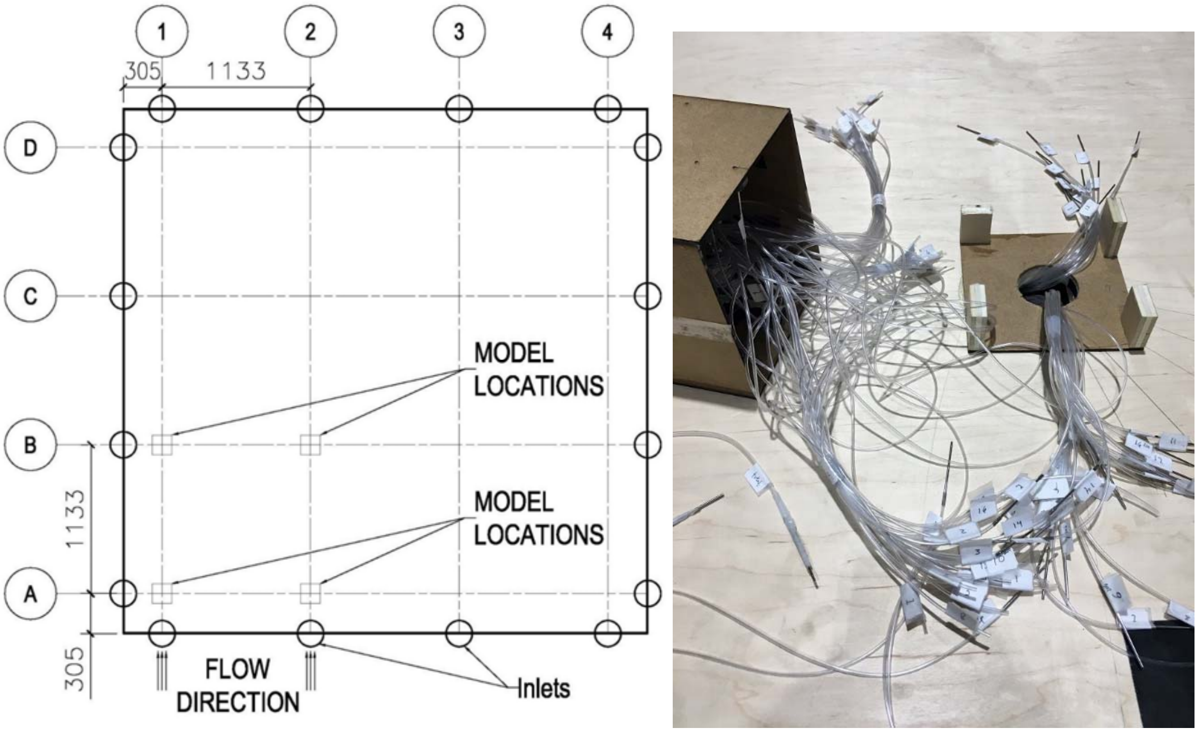

Figure 5:  Testing plan view and the Silsoe Cube model

At this stage, it was assumed that the unidirectional and the shear flow incoming through the inlets would be straight and perpendicular to the inlet sections. The flow would remain steady for a certain distance after the inlet. Secondly, exploring the differences between the straight flow along gridline 1 and gridline 2 is intended, as they are obviously spatially different. Future research plans include investigation fo the effects of the flow from two perpendicular inlets. For instance, the cube model at A1 is affected by the flow along gridline 1 and gridline A simultaneously.

The pressure measurements were recorded at the same place on the Silsoe cube model as in the full-scale experiment. 18 pressure taps are distributed at the centerline on the front, top and back surfaces of the cube. Another 24 pressure taps are also placed horizontally at the centerline of the four vertical surfaces of the cube. The spacing between each pressure tap is 0.173 of the cube length and the edge of the cube to the nearest pressure tap is 0.066 of the cube length. The fixing components under the cube mode would allow the cube model to be rotated on the artificial floor. By rotating, the windward flow angle ϴ Figure 6 of the Silsoe cube can be adjusted. In this experiment, all the Silsoe cube models were tested with four wind flow angles: 90°, 75°, 60° and 45°. Less than 45° cases wouldn't be necessary due to the symmetry of the cube. The pressure coefficients result of 1:30 and 1:40 scaled model at location A2 and B2 with ϴ=90° flow angle will be illustrated in the following sections.

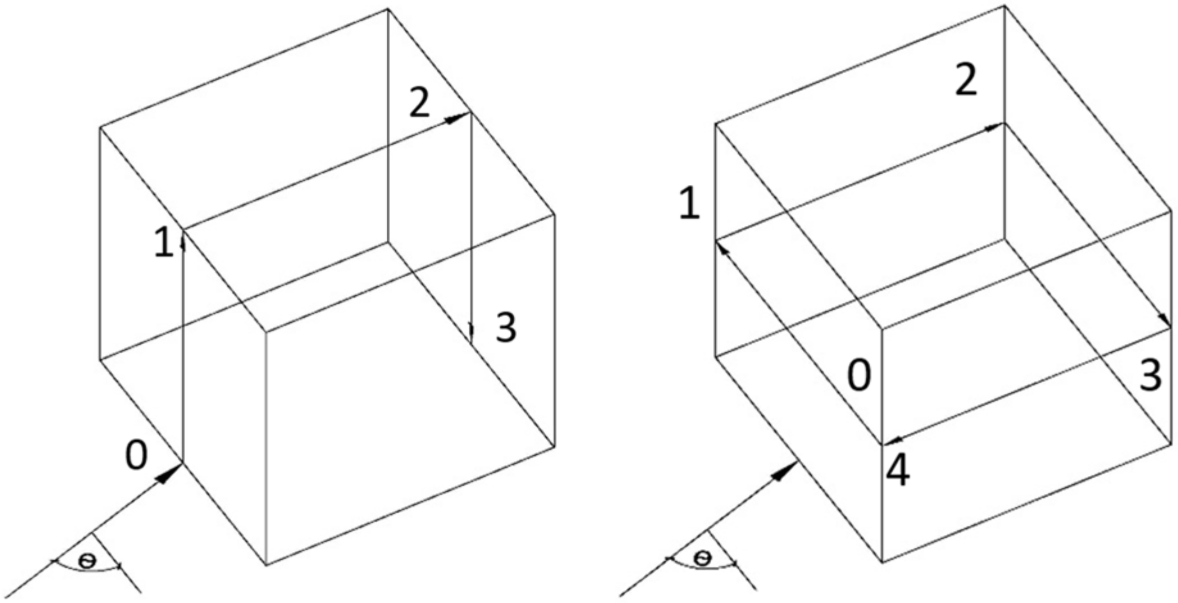

Figure 6: Flow angle and measurement directions: vertical ring (Left) and horizontal ring (Right)

The pressure coefficient is used to illustrate the corresponding pressure within a relatively low-speed incompressible flow fluid field. The mathematical expression of the coefficient is shown as follows (Fluid mechanics 1973):

[2] $C_p = \frac{p - p_\infty}{1/_2 \rho_\infty V_\infty^2}$

Where the Cp is the pressure coefficient, p is the static pressure at the assessed location, $p_\infty$ is the static pressure in the stream, $\rho_\infty$ is the stream fluid density of 1.225kg/m$^3$, and $V_\infty$ is the stream flow velocity measured simultaneously with the static pressure p. During the test of the scaled substitute, the $C_p$ is supposed to be the same as the $C_p$ which was measured in the full-scale application.

### 3.2 Pressure Coefficients Comparison

As specified above, the test results at the location A2 and B2, as represented in Fig. 5, for 1:40 and 1:30 scaled models and 90 flow angle will be discussed. The flow velocity used in the experiment is 5.7 m/s, which is similar to the averaged wind velocity during the full-scale test conducted for the Silsoe cube (Richards 2012). The results at one location, were averaged from 1,200 samples measured at the pressure tap by the pressure scanners within 4 minutes after the pressure became steady in the WDS. Samples at different locations on the cube were measured simultaneously. The pressure coefficients as shown previously were calculated based on the pressure reading on the certain locations of the cube divided by the dynamic pressure which was derived from the equation [1].

The results of both scales at the location A2 are shown in Figure 7. Blue diamond curve represents the pressure coefficients from the full-scale test. For the vertical ring, the pressure coefficients at the windward face, location 0-1 in the plot, of the cube of both scales agree well to the full-scale results. Meanwhile, at the roof and leeward face of the cube, location 1-3 in the plot, the pressure coefficients of the scaled cubes didn't vary as in the full-scale test and were higher than the full-scale results however were close to 0. This indicates that only minor pressure changes were induced by the flow at those two surfaces along the vertical ring direction. The measurement at the horizontal ring was showing the similar pattern. Only the pressure coefficients at the windward face of the scaled cubes, location 0-1 in the plot, was in good agreement to the full-scale results while the left face, leeward face, right face, location 1-4 in the plot, had negligible pressure change during the test. Thus, location A2 was not able to generate similar pressure distribution to the overall surfaces of the scaled cube.

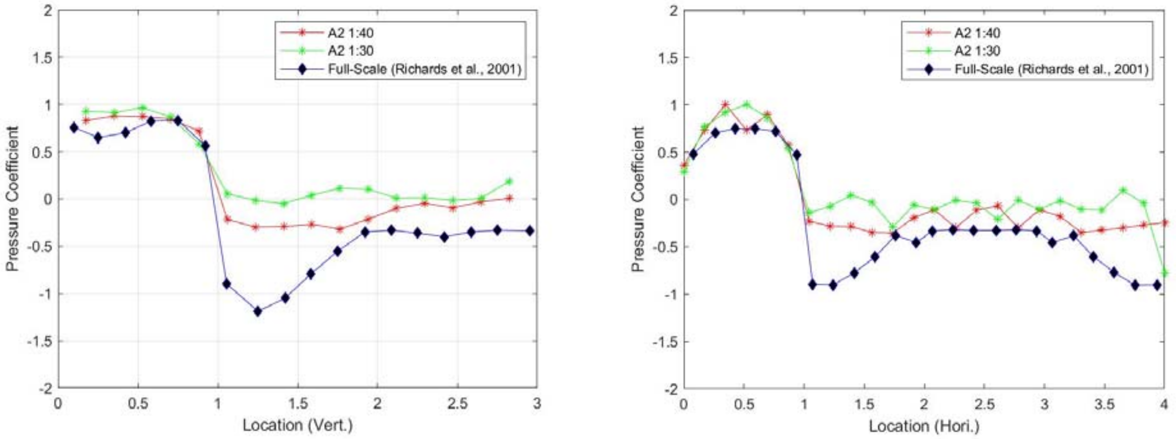

Figure 7: Pressure coefficient results at location A2: vertical ring (Left) and horizontal ring (Right)

Location B2 was further from the WDS inlet comparing to the location A2 (Fig.5). In Figure 8 the pressure coefficients measured for the 1:30 scaled Silsoe Cube were demonstrating the same type of discrepancy when compared with the full-scale results either on the vertical ring or the horizontal ring. On the other hand, the pressure coefficients of the 1:40 scaled Silsoe Cube model was showing almost the same pattern as in the full-scale test from location 0-3 on the vertical ring and location 0-4 on the horizontal ring. Therefore, the full-scale Silsoe Cube pressure distribution could be reproduced in the WDS at the location B2 for the 1:40 scaled Silsoe Cube model.

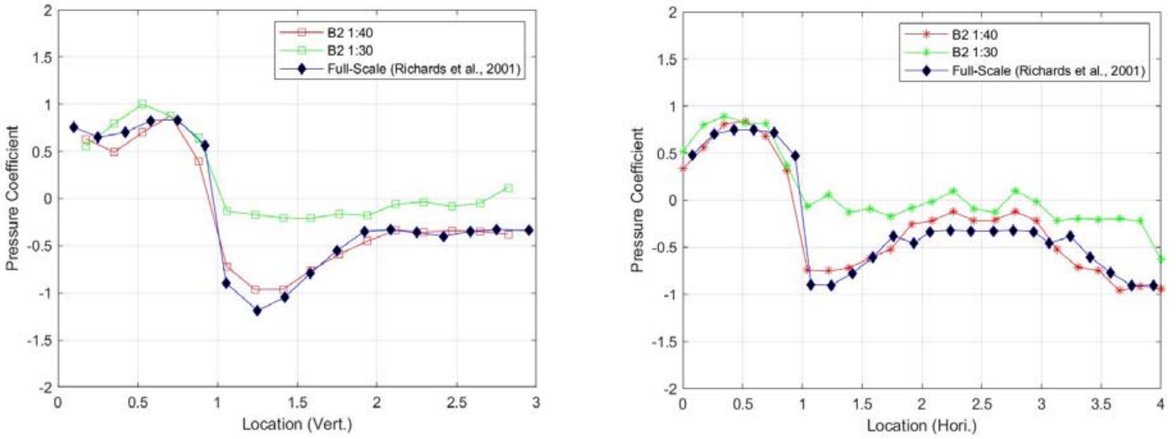

Figure 8: Pressure coefficient results at location B2: vertical ring (Left) and horizontal ring (Right)

The 1:30 scaled Silsoe Cube pressure coefficients was different from the full-scale results on the four measured faces. This was mainly due to the size of the 1:30 scaled cube which is larger than the cross-section of the inflow at the location A2. The differences on the roof of the model and the leeward face at the location A2 between the 1:40 scaled cube and the full-scale results was also caused by the same reason. Moreover, the 1:40 scaled cube result showed a significant improvement when it was at the location B2. The cause of such improvement of the 1:40 scaled cube is that after the wind flow went through the circular inlet, the large empty space in the WDS allows the inflow to be dissipated. Consequently, the flow cross-section expanded and it is able to cover the entire 1:40 scaled cube.

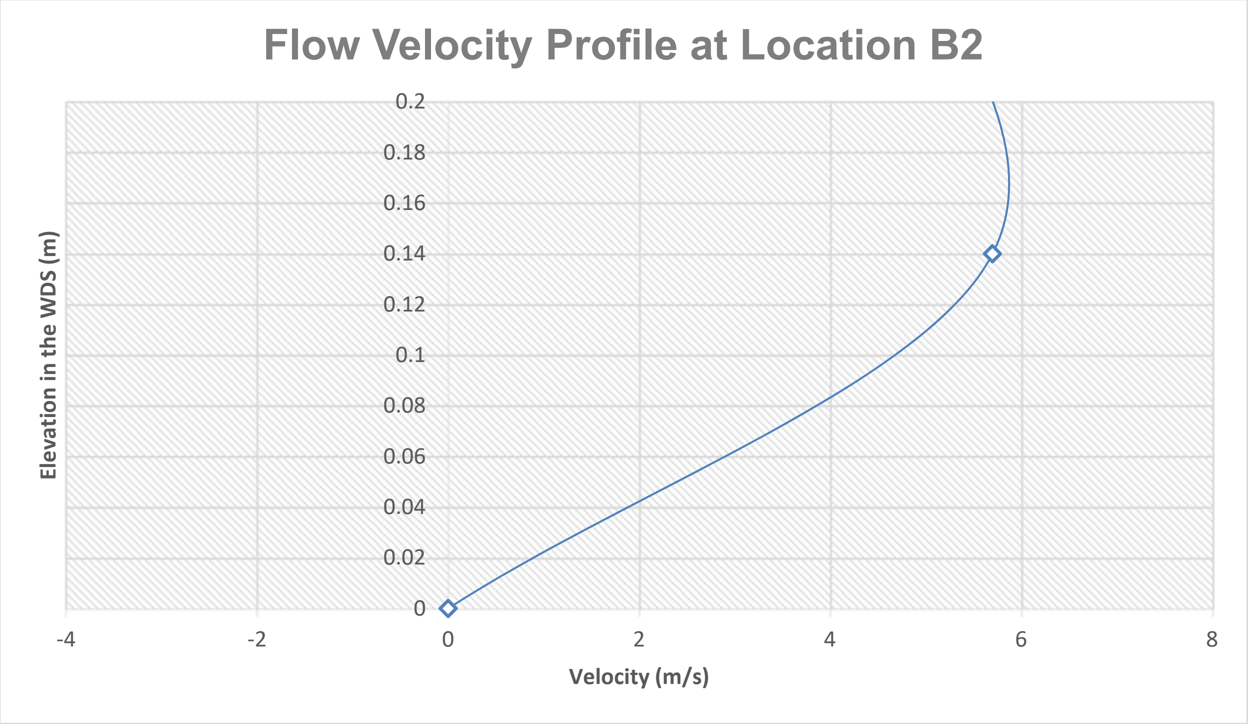

Figure 9:  Flow velocity profile at the Silsoe Cube model in the WDS

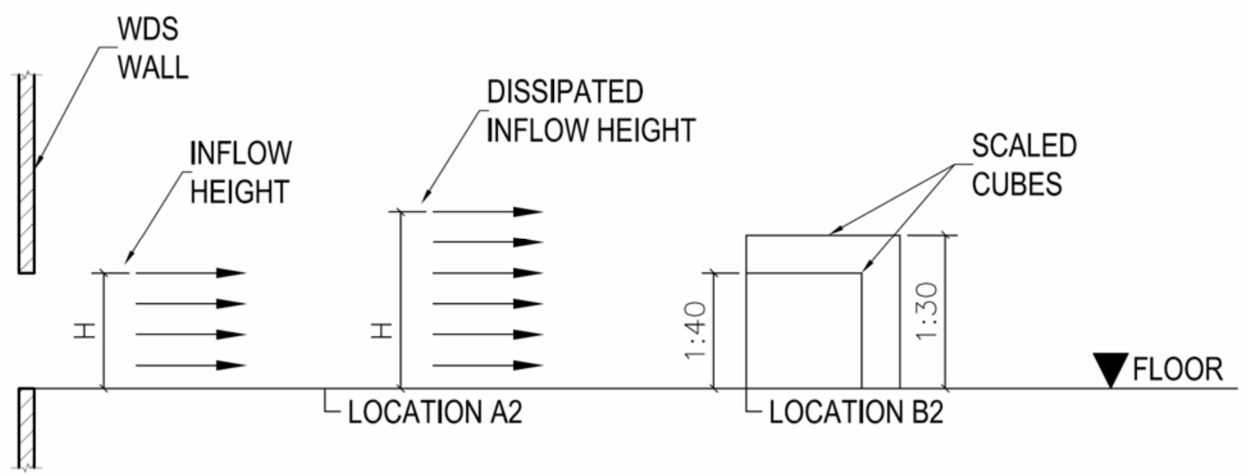

Figure 10: Schematic of the inflow vs the scaled cube at different locations

## 4 Conclusion

The pressure coefficients distribution for the1:40 scaled Silsoe model at the location A2 and the 1:30 scaled model at location A2 and B2 were not in good agreement with the full-scale results, while the 1:40 scaled model at the location B2 is in good agreement to the full-scale Silosoe Cube pressure coefficients distribution. The cause of the discrepancies was mainly due to the cross-section area of the generated shear flow was not large enough (as shown in Figure 10) to cover the entire scaled model at designated locations. Nevertheless, if the proper scale is assigned to the tested model, combined with an appropriate testing location in the WDS, the simulation of the averaged pressure distribution on the structure can be implemented.

## 5 Acknowledgement

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