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An exploratory study on wind speed profiling of high-rise building/monument using EnviMET

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Abstract
Envi-MET is a useful tool for simulating wind speed at building heights and modelling microclimatic conditions around buildings, including wind speed around buildings and other structures. Envi-MET is used in this study to simulate wind speed toward building heights. When R2 = 0.8186, relative bias is -0.0775, and RMSE is 0.2578, the agreement between Envi-MET simulation and ground observation indicates acceptable agreement. With this establishment, it was discovered that the building's height and wind speed are not the only factors causing destruction; the less friction of wind with surface features will also increase the wind speed, as shown by the results of the vertical profile wind speed in relation to the tollway building's height. At a height of 13 metres, the wind speed is 3.5 m/s. Wind circulation affects the building at this elevation, causing damage to the roof and ceiling. Buildings and structures can sustain significant damage as a result of high wind speeds. When wind speeds are high, the wind's force increases, causing pressure differences on different sides of a building or structure. The findings of this study inform relevant parties of the impact of wind on building construction and how it may influence variations in wind speed.

Keywords: Windstorm, Envi-MET, Coriolis force, turbulent drag, Wind disaster

INTRODUCTION

Wind is the flow of air relative to the Earth's atmosphere. It is caused by a force acting on it, as is the case with all moving things. According to Wang et al. (2020), a force is a pull or push that modifies the resting state, motion, or direction of an object. Wind speed can cause building destruction in several ways. Strong winds can create high-pressure zones on one side of a building and low-pressure zones on the opposite side, resulting in unbalanced forces that can cause the building to sway or vibrate. This might cause structural damage, possibly even causing a building component to crack or break or even to collapse (Taranath, 2021). Strong winds can blow objects into buildings, such as tree branches, signboards, or loose building parts, in addition to the direct wind pressure. This can cause physical damage to the building's exterior and windows, and potentially cause injury to people inside the building.

Furthermore, wind-induced vibrations can cause fatigue damage to building components over time, especially in tall buildings or those with slender components like beams or columns (Lago, Trabucco, & Wood, 2019). Tall or slender buildings are more susceptible to wind-induced damage or destruction due to their increased height and flexibility. Wind tunnel testing and other wind engineering studies can help identify potential wind-induced damage and provide recommendations for building design, materials, and construction methods to reduce the risk of failure. This can lead to cumulative damage and eventual failure if not addressed. To prevent wind-induced building destruction, building codes and standards typically require buildings to be designed and constructed to withstand specific wind loads based on the local wind speed and other factors (Mendis et al., 2007) . Engineers use wind speed data to calculate wind loads and design building components that can resist those loads. In addition, regular inspections and maintenance of building components can aid in identifying and addressing potential damage caused by wind or other elements.

There are several areas around the world that are prone to high wind speeds, including:

1. Coastal regions: Coastal regions are often subject to strong winds due to their proximity to the ocean. Regions situated along the Gulf Coast of the United States are subject to regular occurrences of hurricanes and tropical storms, characterised by elevated wind velocities and storm surges.
2. Mountainous regions: Mountainous regions can also experience high wind speeds due to the funnelling effect of the terrain. Wind speeds can increase as the wind is channeled through mountain passes or over ridges. The Rocky Mountains in the western United States are one example of a region prone to high wind speeds.
3. Polar regions: Polar regions can experience strong winds due to the temperature differential between the cold air at the poles and the warmer air at lower latitudes. The polar jet stream can bring high winds to areas near the poles as well as to areas further south.
4. Tornado Alley: Tornado Alley is a region in the central United States that is prone to tornadoes, which can bring high wind speeds and cause significant damage. Tornado Alley includes parts of Texas, Oklahoma, Kansas, and Nebraska.
5. Cyclone-prone regions: Cyclones, also known as typhoons or hurricanes, can bring high wind speeds to coastal regions in many parts of the world, including Southeast Asia, the Caribbean, and the Gulf of Mexico.

In areas prone to high wind speeds, building codes and regulations may require specific wind-resistant construction. A decrease in albedo leads to an increase in mean wind speeds and the frequency of high wind speeds along with increased turbulent energy in the planetary boundary layer n techniques and materials to ensure building safety and prevent destruction (FEMA, 2018). Previous study has investigated the dynamics of land surface albedo and temperature (Salleh et.al, 2022). A reduction in albedo results in elevated mean wind velocities and heightened occurrence of strong wind speeds, accompanied by amplified turbulent energy inside the planetary boundary layer.

Apart from that, there is no denying the benefits of wind for urban cooling purposes. Study by (Isa et al,, 2020) concerns the effect of urbanisation at Greater Kuala Lumpur that leads to Urban Heat island (UHI). The use of wind to ventilate and cool the city was needed. Even if the wind are less than 10 m/s, it has led to destruction of monuments and buildings in

Malaysia especially in urban areas and residential areas (Zakaria et al., 2019). The process of wind deflation caused the land surface to become armoured, leading to a subsequent rise in both average wind speeds and gustiness. This statement highlights that the albedo, ascertained by analysing the surface geology in this context, may exert positive feedback on wind velocities. The perturbation in albedo as a result of wind erosion activates the feedback mechanism.

Winds are a natural disaster that almost every country on Earth has to deal with. Because of this, there has been a lot of study and analysis. The complicated wind activity that causes windstorms has caused damage to both public and private property. Numerous websites assert that urban areas are frequently impacted by windstorms. More and more often, windstorms kill people and damage or destroy both public and private property. In the Emergency Incidents Database (EM-DAT), the Centre for Research on the Epidemiology of Disasters (CRED) revealed that storm damage was worse in 2017 than in 2016 (Kishore et al., 2018). As an example, Hurricane Katrina in 2005 caused overall financial losses of around 108 billion USD, making it the most expensive natural disaster in the United States. The direct and indirect damage caused by the storm halted the progress of Gulf Coast states. People claim that Sandy and Ike were the second and third costliest storms in history. In 2012, Hurricane Sandy cost $71.4 billion, and Hurricane Ike cost $29.5 billion (Blake et al., 2007). About 13 billion Euros worth of economic damage was done. (Ulbrich et al., 2001).

Typhoon Haiyan, also called Super Typhoon Yolanda, hit the Philippines in 2013. It was called the most powerful tropical storm to ever hit land. The typhoon's strong winds and storm waves caused a lot of damage in southern Asian countries. The total cost of the damage was expected to be about $2.86 billion. Damage from windstorms depends a lot on the physical factors of an urban area (Střelcová et al., 2009). Small hazard events like local windstorms are becoming more important to human security. They have the ability to cause even bigger problems by destroying people's possessions and key infrastructure, which lowers the threshold of resilience in local communities (Kasperson et al., 1996). Windstorms have significant consequences in metropolitan areas. High winds may cause deaths, uproot trees, and cause significant structural harm to homes, power and telecommunications lines, radio masts, and other urban infrastructure. Small variations in temperature and climate extremes have the ability to wreak havoc on structures designed to survive previous climate extremes (Adelekan, 2012). In Australia, building damage increased by 650% for every 25% increase in high wind gust speed (Coleman, 2003). The International Group for Wind-Related Disaster Risk Reduction (IG–WRDRR) was started in June 2009 by the United Nations International Strategy for Disaster Reduction Secretariat (UN–ISDR) in response to a growing understanding of the social and economic effects of severe wind events at the international level. One of the main goals of IG–WRDRR is to use the Hyogo Framework for Action to reduce the risk of disasters caused by wind.

The wind is generally light and variable throughout Asia, Africa, North America, South America, Antarctica, Europe, and Australia. Throughout the observation time, an easterly wind blew at lower latitudes. As North-eastern winds blew in the Northern Hemisphere and southeast winds blew in the Southern Hemisphere, air converged along the equator, creating the Intertropical Convergence Zone just north of the equator (ICTZ) (Wu, 1997). However, there are several seasonal variations in flow patterns, and four seasons may be differentiated from these wind flow patterns, including the Southwest Monsoon, the Northeast Monsoon, and two shorter Inter-Monsoon seasons (Rasyidah & Othman, 2010). During the Southwest

Monsoon, the predominant wind is light, averaging less than 15 knots (7.7 m/s) (Gasing, 2015). During the Northeast Monsoon, sustained winds of 10 to 20 knots (5.2 to 10.3 m/s) prevail, with gusts of up to 30 knots (15.4 m/s) over Peninsular Malaysia's east coast states. The winds are usually light and unpredictable throughout the two Inter-Monsoon seasons (Rasyidah & Othman, 2010). The Malaysia Meteorological Department states that on September 15, 1992, the highest average daily wind speed was 3.8 m/s in Mersing, Johor, and the highest maximum wind speed was 41.7 m/s in Kuching, Sarawak. (MetMalaysia) (Nizamani, et. al, 2018). In 2018 total damages in Malaysia due to windstorm hazards were 53, and some of the cases resulted in fatalities.

The Malaysian Meteorological Department (MMD) is the government agency in charge of informing Malaysians about impending weather conditions, such as windstorms, through television, social media, and websites. Malaysia currently lacks a comprehensive database of windstorm incidence and injury (Wan Chik et al., 2014). The full extent of the windstorm's impact will be beneficial to society, both in terms of emergency response plans and future planning and growth. The urban metropolitan population has been significantly impacted by the windstorm outbreak. According to a study by Zakaria et al. (2019), the seasonal monsoon has some relationship with windstorms in Malaysia. The study looks at the effects of the Southeast Monsoon, the Northeast Monsoon, and the time between the two. The strongest windstorm was during the Southeast Monsoon. The Northeast Monsoon had the fastest wind speed, which was between 5.96 and 6.23 m/s. Southeast Monsoon winds blow the fastest and have the most effect on the land north of the peninsula. Their speeds range from 9.20 to 10.96 m/s. Windstorms in Peninsular Malaysia were to blame for 80% of roof damage. The reason was that big towns were getting more and more people, which meant that high-impact facilities and services were getting closer together (Tao, 2013). A study done in Pulau Pinang between 2010 and 2013 found that steel sheet roofing caused 47% of the damage, the truss system caused 30%, roof tiles caused 13%, and other parts caused 20% (Majid et al., 2016).

Envi-MET proposes a method for designing the metropolitan landscape to have the best available microclimate environments for inhabitants, which is critical for human safety. It is possible to determine the impact of wind gusts caused by jet impacts at building corners (Huttner et al., 2008). Environmental planning and developers will get a decent standard in urban environments and be mindful of the urban microclimate through the Envi-MET initiative (Langer et al., 2012). The microclimate model in three dimensions Envi-MET is a model for simulating microscale atmospheres in urban environments with a standard spatial resolution of 0.5 to 10 m and a time resolution of 10 seconds. Envi-MET is a predictive model focused on fluid and thermodynamic fundamental laws. Heat and water vapour exchange processes at the ground surface and at walls, vibration, exchange at the soil, and vegetation parameters are all simulated in this software. Under various mesoscale settings, Envi-MET investigates the impact of small-scale improvements in urban architecture (e.g., trees, backyard greening, modern building constellations) on microclimate.

Temperature, wind direction and intensity, evaporation, relative humidity, and sunlight period are all important meteorological measures (Yan et al., 2019). Sealed surfaces, for example, have a detrimental impact on the local atmosphere because they heat up quickly during the day and cool off steadily at night. Furthermore, the ability of such areas to filter air contaminants and attach dust particles is very limited. The removal of open/green areas, emissions, and barriers to air exchange systems (such as building structures) all have an adverse effect on the microclimate (Liu & Shen, 2014). Thus, this analysis looks at wind speed on a microscale. Since there was no ground station to determine wind speed, the alternate method of using Envi-MET to model the actual event was selected. The total number of Meteorology Department stations that can record wind speed in Selangor, Malaysia, is fewer than 20. Currently, only a few stations have complete wind speed records. Every station's coverage area is much too broad to be useful in certain regions. In this analysis, the effect of wind on man-made features was established.

METHODOLOGY

Study Area

Due to a storm event reported on August 24, 2018, which took place during the Southeast Monsoon season, the Bukit Raja Toll Plaza was chosen as a study area (Harian, 2018). Bukit Raja is located in the Klang district with latitude and longitude: 3.0734° N, 101.4752° E and part of Klang, Selangor, as shown in Figure 1, with an average wind speed of 1.6 m/s to 2.7 m/s (METMalaysia, 2018). The studied area is surrounded by industrial zones and toll roads. The total study area encompasses roughly 17,38 hectares. Bukit Raja Tol measured approximately 80 metres in length and 13 metres in height.

Around 9 p.m. on August 24, 2018, a storm destroyed Bukit Raja Toll, causing damage to the roof and structure of the building. During the event, a public witness reported that the wind was blowing significantly harder than usual (Astro Awani, 2018). Figure 2 shows the damages caused by the event. The report shows the top siling falling and a few monuments damaged. Thus, the microscale simulation of wind speed in Bukit Raja Toll was carried out on the same date of event to study the approximate wind speed during the event using Envi-MET simulation. 24-hour data was analysed for 24 August 2018 with different heights from 0 metres to 13 metres.

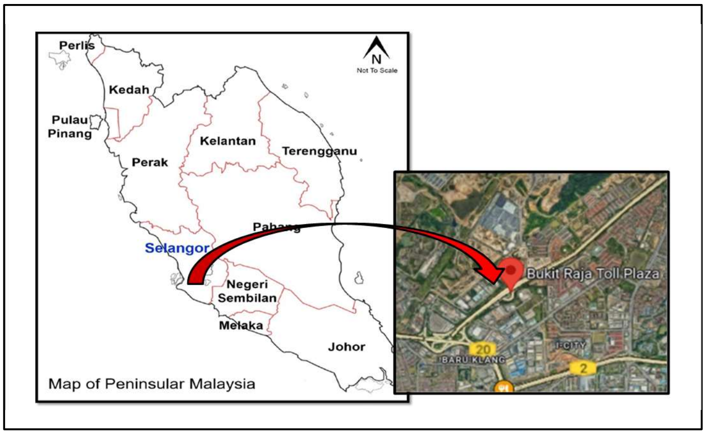


Figure 1. Study area at Bukit Raja Toll (Google, 2020)

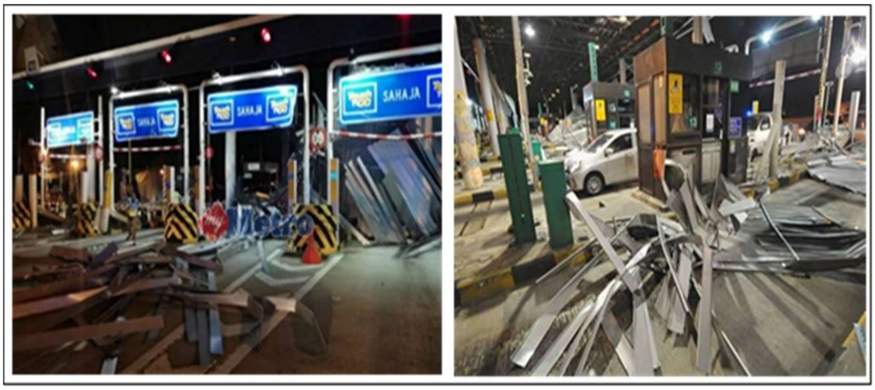


Figure 2. Damage at Bukit Raja Toll Plaza on 24 August 2018 reported by Berita Harian newspaper (Harian, 2018)

Envi-MET Simulation

Envi-MET version 4.1 was used to simulate the wind speed for this study. Due to the software's capability to simulate microclimate, Envi-MET's is used to simulate the microclimate study. Envi-MET is a computer program designed to simulate the urban microclimate. Envi-MET is a helpful program to simulate the urban climate in cities and can assist with environmental planning (Chatzinikolaou, Chalkias, & Dimopoulou, 2018). The 24-hour data was simulated on 24 August 2018. The simulation size was a 50 x 50 x 40 grid with 1 grid equivalent of 10 metres. Therefore, the total size of the simulation was 500m x 500m x 400m. This is the maximum size that can be conducted due to licensing restrictions while using the Envi-MET.

Figure 3 shows the Envi-MET simulation workflow. 3D modelling of study area was created using Envi-MET tool, as shown in Figure 4. A Google map image was used as a reference while designing the study area model. The model was simulated using the real environment representation criteria, such as the model geometry, model location, material of building, the height of building, type of vegetation and type of soil, as well as the real meteorology data ENVI-met databases provide a variety of materials and 3D plants, allowing the detailed reconstruction and accurate modeling of the urban environment. The climatic data input for the simulation were the minimum and maximum wind speeds on the day between 1 m/s and 2 m/s, the temperature between 28˚C to 35˚C, and the direction of wind at 345° as shown in Table 1. For the height of the building, it follows the real height in ground data, such as toll monument height of 13 metres, then, inside the model, 13-metres. The element type uses of the built environment are illustrated in Table 2. For the building element, the concrete wall (cast dense) was selected. For the type of soil and surface, this model uses asphalt road and soil and vegetation using grass, vegetation with a height less than 0.5 metres and a few above 2-metre height trees.

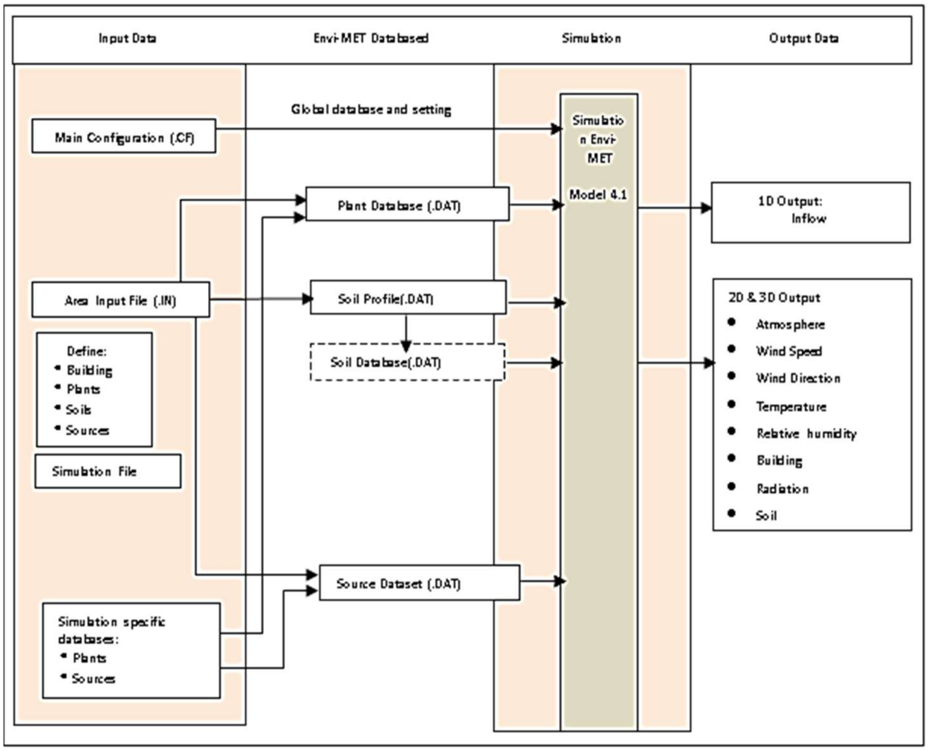


Figure 3. Envi-MET simulation workflow

Figure 4. Bukit Raja Toll from google earth image was modelled into the SPACE tool in Envi-MET software.

Table 1. Data input to Envi-MET model.

Data Input	Value
Simulation Date	24 August 2018
Start & Duration of Simulation	00:00, 24h
Minimum Wind Speed	1 m/s
Maximum Wind Speed	3 m/s
Minimum Temperature	28˚C
Maximum Temperature	35˚C
Direction of the Wind	345°
Minimum Humidity	60%
Maximum Humidity	90%

Table 2. Element type of build environment

Element	Type
Building Wall	● Concrete wall (cast dense)
Soil and Surface	● Asphalt Road ● Soil
Vegetation	● LAD lower 0.5 meter ● LAD above 2.5 meter ● Grass

Ground Station and Envi-MET Data Validation

The compatibility between ground station data and Envi-MET simulation has been determined. This comparison to test the accuracy of Envi-MET software to conduct the microscale simulation for wind speed. The available ground data on 24 August 2018 was used to validate with Envi-MET simulation. This validation purposely checks the accuracy of Envi-MET simulation compared to ground station data. Using domain 20 x 20 x 20 grids which is 1 grid equal to 2 metres, the ground station was modelled in 3D into Envi-MET software at height 4 metres, following the real data. Figure 6 shows the study area ground station in SPACES tool was modelled from google earth image in format .BMP.

The criteria approximated the real environment, such as the model geometry, model location, material of building, the height of building, type of vegetation and type of soil. To simulate the model, the real meteorology data was used. Then, the model was imported to ENVI-Guides and given the real meteorology data configurations. The minimum and maximum wind speed on the day between 1 m/s to 2 m/s, the temperature between 28˚C to 35˚C, and the direction of wind at 310° were used for the simulation. The simulation was carried out using the Envi-MET tool. The map of wind speed by each height was generated, and the analysis of data was carried out in the LEONARDO tool. The variations in the accuracies of wind speed and energy efficiency between ground measurement and Envi-MET simulation were quantified using statistical methods. Equations (1) and (2) were used to quantify the bias and root mean square defect, respectively:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(f_i - o_i)^2} \qquad \text{Eq. 1}$$

Where:

- n: number of samples
- f: forecasts
- o: observed values

$$RE = \frac{\sum_{i=1}^{n}(P_i - O_i)}{\sum_{i=1}^{n} O_i} \qquad \text{Eq. 2}$$

Where:

- Oi is the observation value
- Pi is the forecast value.

METHODOLOGY

Validation of Ground Station vs Envi-MET Simulation

The calibration between ground data and the Envi-MET simulation was established. The purpose of this calibration is to prove the efficiency of Envi-MET simulation to substituting ground data due to the absence of data for certain areas. Generally, Malaysia lacks ground stations, and some of them are unable to give continuous readings. Hence, the nearest ground station at SK TTDI Jaya station on 24 August 2018 was used to validate the Envi-MET simulation, and the results were compared.

Table 3 shows the wind speed reading (m/s) from ground observation and Envi-MET simulation. Since the height of ground station equipment was 4 metres, the simulation at Envi-MET also used the same vertical height at 4 metres during the simulation. The pattern of wind speed from both ground observation and Envi-MET was shown in figure 5 and Figure 6. As a result, from the statistical calculation, the highest residual was 0.266 at 4.00 a.m.,m and the lowest residual was -0.715 at 3.00 p.m.. From the result, the positive value shows the observation value is higher than Envi-MET and vice versa. Figure 7 shows the agreement between Ground Observation and Envi-MET simulation on 15 April 2017 (SK TTDI Jaya station). The graph indicates that the R2 value is 0.8186, which is closest to 1. A similar study by (Bande et al., 2019), where the R2 value is more than 0.5, therefore the reading of wind speed from Envi-MET simulation can be accepted for this study. The Root Mean Square Error (RMSE) and Bias value were 0.2578 m/s and -0.0775m/s. RMSE is between 0.2 to 0.5 shows that the model fits this study (Chatzinikolaou et al., 2018) . The lower the RMSE, the better the model and its predictions. A lower RMSE indicates that there is a small deviation from the residual to the ground truth (Hien, Ignatius, Eliza, Jusuf, & Samsudin, 2012).

Based on the RMSE and Bias tolerance, this analysis determined the exceptional agreement between the simulation and the ground observation. Therefore, the Envi-MET simulation model can be used in this study to simulate the wind speed in a microclimate area.

The model was implemented for the study area, the Bukit Raja Toll Plaza on 24 August 2018. There were windstorms reported by the media that caused destruction (Astro Awani, 2018). Therefore, the model was used to see the vertical profiling of wind speed impacts towards the building.

Table 3. Comparison between Ground Observation and Envi-MET simulation for SK TTDI Jaya Station on 15 April 2017

Time	Observation	Envi-MET	Residual	Square
1:00:00	0.179	0.2	0.0210	0.000441
2:00:00	0.432	0.402	-0.0300	0.0009
3:00:00	0.326	0.546	0.2200	0.0484
4:00:00	0.569	0.835	0.2660	0.070756
5:00:00	0.455	0.596	0.1410	0.019881
6:00:00	0.414	0.324	-0.0900	0.0081
7:00:00	0.045	0.208	0.1630	0.026569
8:00:00	0.29	0.357	0.0670	0.004489
9:00:00	0.265	-0.275	-0.5400	0.2916
10:00:00	0.164	0.145	-0.0190	0.000361
11:00:00	0.322	0.157	-0.1650	0.027225
12:00:00	0.534	0.159	-0.3750	0.140625
13:00:00	0.98	0.653	-0.3270	0.106929
14:00:00	1.059	0.654	-0.4050	0.164025
15:00:00	1.521	0.806	-0.7150	0.511225
16:00:00	1.57	1.223	-0.3470	0.120409
17:00:00	1.586	1.695	0.1090	0.011881
18:00:00	1.541	1.526	-0.0150	0.000225
19:00:00	1.068	1.041	-0.0270	0.000729
20:00:00	1.206	1.127	-0.0790	0.006241
21:00:00	0.901	0.913	0.0120	0.000144
22:00:00	0.152	0.316	0.1640	0.026896
23:00:00	1.515	1.594	0.0790	0.006241
24:00:00	1.915	1.946	0.0310	0.000961
			RMSE	**0.2578**
			Relative Bias	**-0.0775**

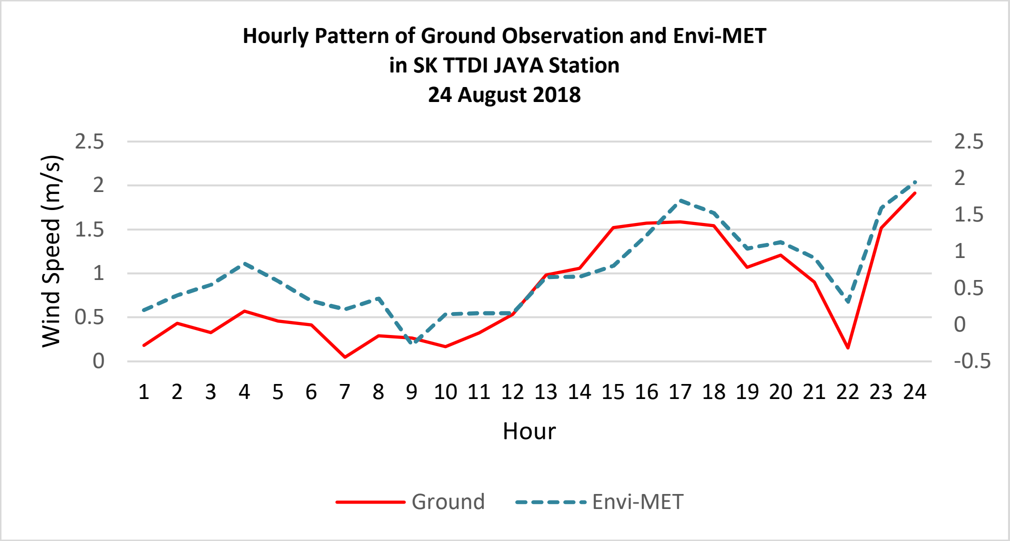


Figure 5. 24-hour Wind Speed pattern between Ground Observation and Envi-MET simulation on 24 August 2018 (SK TTDI Jaya station)

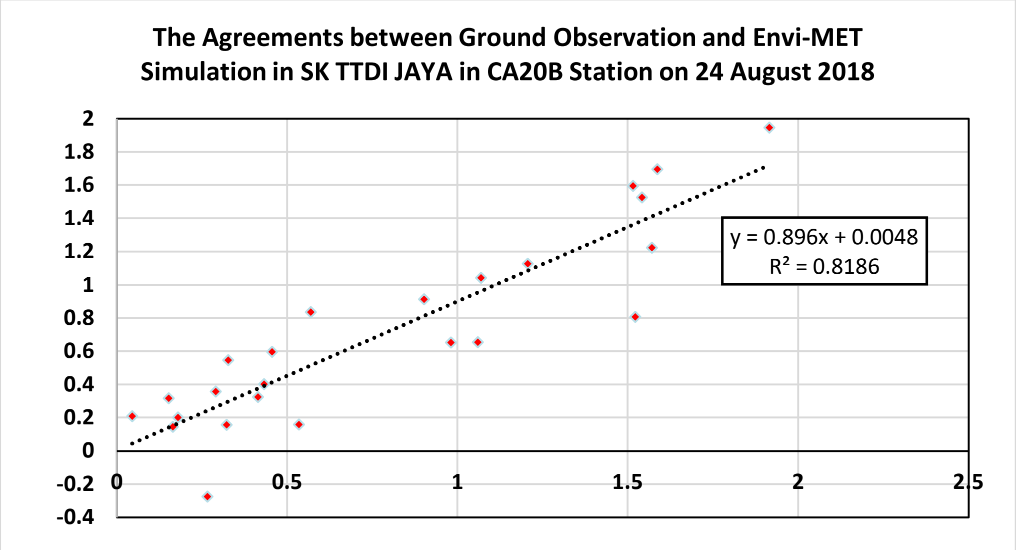


Figure 6. The agreement between Ground Observation and Envi-MET simulation on 24 August 2018 (SK TTDI Jaya station)

Wind Speed of Bukit Raja Toll from different height

The simulation was conducted for twenty-four hours on August 24, 2018. To determine changes in wind speed, the model was simulated at various heights. As shown in Table 4, the k value in Envi-MET was modified from 0 to 1, 2, 3, 4, 5, 6, 7, 8, and 10 to represent the height of the model. Height was used to generate graph analysis. Since the destruction was recorded at 9 p.m., the analysis focuses on that time (Harian, 2018). The minimum wind speed at 9.00pm during the event was 0.095 m/s and the maximum wind speed was 2.149 m/s. Generally, with the speed below 10 m/s of wind speed is considered as a light breeze following world Beaufort scale and should not cause any destruction. Unfortunately, for this study area and date, there was destruction recorded. Therefore, the profiling of each height was investigated to define the factors that caused the damages to the Bukit Raja Toll Plaza on 24 August 2018 at 9.00pm.

Table 4. k values and the height in metre with wind speed at 9.00 pm during the event

k ***(Value of height use in Envi-MET)***	**Height (0-metres from ground in real world)**	**Wind speed (m/s) at 9.00 pm**	
		Minimum	**Maximum**
0	0.2	0.095	1.303
1	0.6	0.096	1.323
2	1	0.097	1.346
3	1.4	0.099	1.365
4	1.8	0.101	1.309
5	3	0.114	1.426
6	5	0.135	1.476
7	7	0.186	1.557
8	9	0.294	1.676
9	11	0.491	1.869
10	13	0.814	2.149

Figure 7 (a) shows the hourly profiles of wind speed using the simulation at height 0.2 metres. The highest wind speed was 2.5 m/s and the lowest value was 0.35 m/s. From the figure (a), the wind speed in front of the toll plaza shows most wind speed readings less than 1 m/s even though the surrounding area of the simulated model shows the reading is above 2 m/s. Wind speed that is below 1 metre usually does not affect the building or monument that is made up of concrete and cement (Atkinson et al., 2009). Similarly, as height 0.6 metres, 1.0 metres, 1.4 metres and 1.8 metres as shown in figure 7 (b), figure 7 (c) and figure 7 (d) there is no significant difference in wind speed reading since there is small increment of wind speed. Wind speed at 2 metres (6.5 feet) height and below can cause minor damage to buildings, especially if the wind speeds are sustained for an extended period of time (Wen, Palanichamy, & Ramasamy, 2019). Wind speeds at these heights are typically lower than wind speeds at higher elevations but can still cause objects such as loose roofing material, siding, or debris to become dislodged and pose a hazard to people and property.

Building codes and regulations typically require buildings to be designed and constructed to withstand certain wind speeds, depending on the location and wind conditions (FEMA, 2018). Wind speed studies are often conducted to assess the potential wind load on a building and to ensure that the building is designed and constructed to withstand the expected wind forces. It's important to note that wind speed alone may not cause significant building damage, as other factors such as building design, materials, and construction quality also play important roles. Additionally, wind direction and duration can also have significant impacts on building stability and safety. The wind speed is dynamic and uncontrolled. It depends on various situations including the high wind load. As a result, it will impact the wind speed to become low or high (K. Kumar, Krishna, & Bhandari, 2012).

Figure 7 (f) shows the map of wind speed when simulation is at 3.0-meter height. The lowest wind speed is about 0.40 m/s, and the highest wind speed was 2.87 m/s. In general, wind speeds at this height are higher than wind speeds at lower elevations, as they are less affected by friction from the ground (Wang, Liu, Li, & Zhao, 2010). In urban areas, wind speeds can be affected by the surrounding buildings, which can cause wind to be funnelled or accelerated through narrow streets and alleyways. However, the effect of ground friction can still have an impact on wind speed and wind direction in urban areas or areas with complex terrain. This can result in higher wind speeds and gusts than would be expected in open areas. The surface roughness of the ground can cause friction and slow down the wind speed near the ground (Zhang, Wang, Chen, Li, & Dickinson, 2019). Therefore, wind speeds at lower elevations are generally lower than at higher elevations, where there is less friction. Wind speed studies are often conducted to assess the potential wind load on a building and to ensure that the building is designed and constructed to withstand the expected wind forces, considering the ground friction and other factors that can affect wind speed and direction.

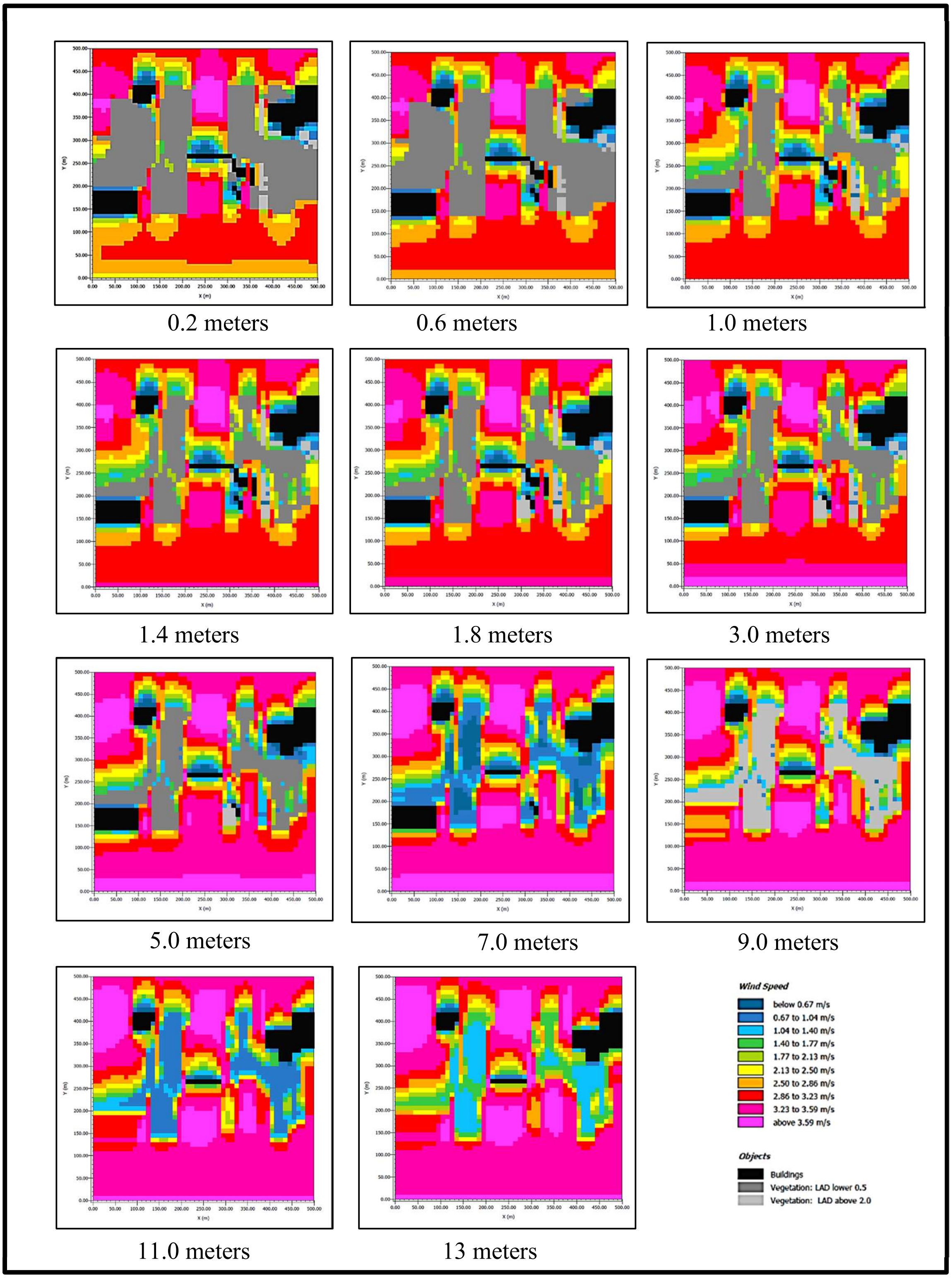
At height 5, 7 and 9 metres, as shown in figure 7 (g), figure 7 (h) and Figure 7 (i), the magenta colour is covering almost the simulation area. The highest wind speed was 3.38m/s. The height is half from the height of toll building 13-metres. As the height of the building rises, the friction of wind toward the horizontal plane decreases. For 7 metre and 9-metre height, the surrounding wind speed shows a 60 % increment of wind speed Wind speed at higher elevations, such as 7 metres and 9 metres height, can be higher than wind speeds at lower elevations, such as 5 metres height. However, the exact wind speeds that can cause building damage can vary depending on several factors, including building design, materials, and construction quality (Fleming, 2015). In addition to wind speed, wind direction and duration can also have significant impacts on building stability and safety. Buildings with sloping roofs, rounded corners, and tapered sides are generally more resistant to wind loads than buildings with flat roofs and square corners (Jagbir & Kumar, 2021). Building shape and orientation can also affect the wind load on a building and should be considered in the design process. In areas prone to high wind speeds, building codes and regulations may require specific wind-resistant construction techniques and materials to ensure building safety and prevent damage (Smith, 2017).These may include using stronger building materials, reinforcing building components, and designing buildings with wind-resistant features such as bracing, anchoring, and overhangs. Building design and materials, as well as wind direction and duration, can also play important roles in building resistance to wind loads.

When k=9 which is 11 metres, wind speed reading during the windstorm event at 9.00 p.m. from the figure 7 (k), the lowest wind speed was 0.60 m/s. The surrounding wind speed was increased to 3.50 m/s. The less friction the wind has with any monument on the surface, the more the wind speed increases, and there is building damage reported at this height. Ground friction is one of the factors that affects wind speed at different heights (Loubere & Fariduddin, 2008). As wind flows over the earth's surface, it interacts with objects on the ground and the surface itself. This interaction creates friction, which reduces the wind speed near the ground. The amount of ground friction depends on several factors, such as the roughness of the terrain, the presence of vegetation, and the type of surface, among others (Zobeck & Van Pelt, 2013). At a lower height, the wind speed is reduced due to the higher ground friction, and the wind flow is affected by the terrain and obstacles such as buildings and trees. However, as the height increases, the ground friction decreases and the wind speed increases, following what is called the wind profile. This means that at higher heights, the wind speed is generally faster and more consistent (Archer & Caldeira, 2009).

At the height of 13 metres at the top of the toll building, wind speed readings during the windstorm event at 9.00 p.m. from figure 7 (l) increased up to 3.59 m/s. At this height, the wind circulation totally impacted the building. The ceiling and the roof fell off and were uprooted from the building. The wind speed at a height of 13 metres can be quite strong, and it is possible for it to cause damage to a building if the building is not designed and constructed to withstand the expected wind forces (Yang, Gao, Bai, Li, & Tamura, 2018). The damage, with the ceiling and roof being uprooted from the building, suggests that the wind forces were very strong and exceeded the building's capacity to withstand them. When wind speeds are high, the force of the wind increases, and it can create pressure differences on different sides of a building or structure (Singh & Roy, 2019). This can lead to structural damage such as bending, twisting, or buckling of walls, roofs, or supports. If the wind speeds are strong enough, entire sections of a building or structure can be ripped off or destroyed. In addition to structural damage, high wind speeds can also cause non-structural damage, such as broken windows, damaged siding, or debris impacts. These types of damage can be dangerous for the occupants of the building or for people in the surrounding area.

Figure 8 shows the maximum and minimum wind speeds versus building height on August 24, 2018 at 9.00 p.m. during the windstorm event. From the graph, it can be seen that the wind speed increases as the height of buildings increases. The minimum and maximum wind speeds show an increment as the height of the building increases. The higher the building is, the more susceptible it is to wind loads. The wind is a complex phenomenon consisting of an infinite range of flow situations, especially with regard to the relationship between structures and wind flows. Wind loads exerted on a building are not stable but extremely fluctuating and dynamic.

Other than the wind force itself, the fluctuating pressure may cause significant damage to infrastructure. One of the ways to safely assume wind pressures is the quasi-steady presumption, by which the building is supposed to be a fixed, rigid body in the wind, and a steady lateral force is the wind pressure exerted on the building. This approach is relevant only if the height is less than 50 metres (Nizamani et al., 2018). The wind is a dynamic phenomenon that unexpectedly varies, consisting of a multitude of eddies of varying sizes and rotational features moving relative to the earth in a general stream of air. These eddies give the wind its rapture, causing variations and contributing to a complex characteristic of flow. At any point, the wind vector can be considered as the sum of the mean wind vector and the fluctuation elements. These elements not only vary with height but also depend on the terrain and topography.



0.2 meters

0.6 meters

1.0 meters

1.4 meters

1.8 meters

3.0 meters

5.0 meters

7.0 meters

9.0 meters

11.0 meters

13 meters

Figure 7. Profile of wind speed from 0.2 metre to 13 metres height at 9.00 p.m. during the event.

(D. Kumar et al., 2021) study shows, the corner of a building also impacts wind loading and reactions to high buildings. The corner with chamfered and recessed patterns will increase the wind load. The suggestion of using a rounded corner pattern will decrease the wind load. Generally, the corner building patterns in Malaysia are chamfered and recessed. This pattern has been one factor that causes the wind load to increase even though the wind speed is lower and leads to destruction.

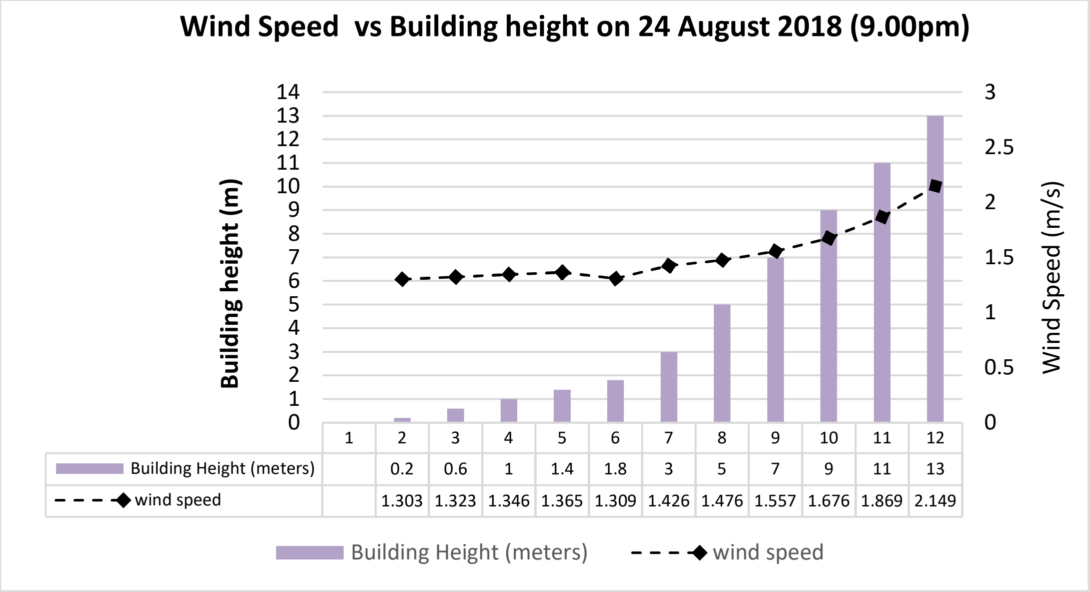


Figure 7. Wind Speed Profile versus building height on 24 August 2018 (9.00 pm) during windstorm event

CONCLUSION

A study on the effects of the height of buildings on wind speed was carried out. It can be concluded that low wind speeds can also cause wind disaster damage and loss. High wind speeds can cause significant damage to buildings and structures, and it is important to design and construct buildings with wind-resistant features to ensure building safety and prevent damage. When wind speeds are high, the force of the wind increases, which can create pressure differences on different sides of a building or structure. This can lead to structural damage, such as bending, twisting, or buckling of walls, roofs, or supports. If the wind speeds are strong enough, entire sections of a building or structure can be ripped off or destroyed. In addition to structural damage, high wind speeds can also cause non-structural damage, such as broken windows, damaged siding, or debris impacts. These types of damage can be dangerous for the occupants of the building or for people in the surrounding area. In areas prone to high wind speeds, building codes and regulations may require specific wind-resistant construction techniques and materials, as well as designs that take into account the wind direction and duration. The aim is to ensure building safety and prevent damage by designing and constructing buildings that are resistant to the wind loads they are likely to experience.

Aside from wind speed, there are a few other factors to consider in windstorm hazard events, such as environmental factors, other meteorological factors, the way monuments are built, and many others. Hence, this study focuses on vertical profiles that cause the wind speed to be high and lead to destruction.

In general, wind speed increases with height above the ground, and this effect is more pronounced in urban areas with tall buildings. This is due to the creation of wind tunnels and other wind patterns that are unique to urban environments. The shape and orientation of the building can also affect the wind flow around it. Tall buildings with flat sides can create large zones of low-pressure areas on the windward side, which can lead to strong and unpredictable wind gusts. These wind gusts can cause damage to the building or objects in its vicinity. The proximity of other buildings can also have an impact on the wind speed near buildings. The interaction between buildings can generate wind vortices or eddies, which can have significant effects on the stability and safety of neighbouring structures. Additionally, computer simulations and wind tunnel tests can be used to model the wind flow around buildings and assess their wind resistance.

Wind speed increases with height above the ground. The wind loads are higher for bigger office buildings because the wind speed is higher. The speed and direction of surface winds are significantly influenced by surface friction. Because the air slows as it moves over the ground, wind speeds are lower than predicted by the pressure difference, and the wind direction changes so that it blows across the isobars into a center of low pressure and out of a center of high pressure.

Since wind in Malaysia is classified as ‘light air’ and ‘light breeze’ based on the Beaufort Scale, it should not cause harm to the environment and destruction. However, there were several wind destruction incidents reported between 2010-2018. This study investigated the factors that contributed to such contradictory wind behaviours. It was identified that the buildings’ height has contributed to the severe condition of ‘light air’. When the wind is blowing towards the house, its force increases from moderate to strong. Anything on Earth's surface, such as grass, trees, and buildings, can cause drag by stopping and slowing the wind. The atmospheric boundary layer (ABL) is the thin layer at the bottom of the atmosphere. It varies in depth from 0.3 km to 3 km. Turbulence in the ABL mixes the very slow movement of air near the top with the faster movement of air in the ABL and slows the wind speed in the full ABL (Nugent & Russell, 2020).

According to the findings, the highest wind speed ranged from 1.303 m/s to 1.476 m/s from 0.2 meters to 5 meters in height. It is brought on by rubbing against structures like buildings, lorries, or anything else that is on the earth's surface. As can be seen from the report, there is less damage at this height. At a height between 7 to 11 metres, the highest wind speed during the event is between 1.557 m/s to 1.869 m/s. The less friction of wind with any monument on the surface, has caused wind speed to increase and there is building damage reported at this height. At the top of the building, 13 metres high, the wind speed during the event was 2.149 m/s. The building is completely affected by the wind circulation at this height. The ceiling and roof were falling and being uprooted from the building.

In conclusion, low wind speeds should not be ignored, especially in densely populated urban areas. Low wind speeds can result in air stagnation, poor air quality, and ventilation problems, all of which can be harmful to building occupants' health. Additionally, low wind speeds can also contribute to the build-up of pollutants and heat in urban areas, creating an urban heat island effect. Even though the wind speed was not very high, damage might have still occurred. In the future, it will be necessary to conduct research on a variety of factors to determine what causes wind damage, including environmental factors, meteorological factors, construction methods, material types, and many others. It is crucial to reduce future damage and the loss endured by relevant stakeholders and the general public.

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