Relationship between wind incidents and wind-induced damage to construction in West Java, Indonesia

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Abstract. In recent decades, the wind has been a major contributor to severe damages to residential constructions in Indonesia. The province of West Java has the highest recorded wind-related damages in the country. Even more, the wind is consistently the second or third source of residential damage, which shows that there is a need to understand the nature of wind as a hazard. However, despite the many cases of destruction due to wind, the data of the destruction is not supported by the wind speed data of the area in question, which makes it difficult to understand how severe the wind condition at the time truly was. Under the classification of the Indonesian National Board for Disaster Management, all cases are classified under severe wind speed or windstorm, even when the wind data is non-existent. This paper explores incidents of wind damages in West Java and matches this data with estimated wind speed conditions obtained from numerical weather model ERA 5. This paper aims to investigate the relationship between wind incidents and wind-induced damage by estimating the wind speed at which wind incidents occur to clarify whether the occurrence is in accordance to the design wind speed, or the strong wind speed definition given by the law. The research was done using field data from the Indonesian National Board for Disaster Management and the West Java Regional Board for Disaster Management. The maximum gust wind speed was estimated from ERA5 reanalysis hourly data. From the analysis of 121 cases between 2011-2018, no gust wind speed that resulted in the damages is above the designated wind speed of 32.1 m/s. Even then, only 2% of the wind speed is above the strong wind definition by the National Board of Disasters at 12.5 m/s. The resulting fragility curve shows that even with a wind speed of 5 m/s and 8 m/s, there is a 50% and 90% possibility of wind-induced damages respectively.

1. Introduction
In recent decades, the wind has been a major contributor to severe damages to residential construction in Indonesia, West Java in particular. The province has the highest recorded wind-induced damages in
the country [1]. Even more, the wind is consistently the second or third source of residential damage, which shows that there is a need to understand the nature of wind as a hazard. Despite the little attention given towards the devastating effects of wind in Indonesia, the numbers show both the potential hazard and the inherent vulnerability of the dwellings that were affected.

Different aspects of wind damages are reported in literatures, corresponding to different hazards, windstorms, hurricanes, or typhoons. Non-engineered buildings are observed to be highly vulnerable to windstorms [2, 3, 4]. Liu and Turner [5] found that wind damages in structures are due to deficiencies in building quality, the lack of building codes, code enforcement, insurance policies, the lack of public understanding, and the lack of adequate research funding. In 1988, extensive residential damages caused by Hurricane Gilbert reveal the lack of modern code provisions in the US [3], showing the importance of wind effects in building codes to assure good performance. Zhang, Nishijima, and Maruyama [6] proposed a model for residential buildings in Japan that considers typhoon-induced wind risk. They concluded that roof tiles and flying debris are weak factors in Japanese residential buildings. Stewart et al. [7] performed fragility analysis for loss of roof cladding in low-rise metal-clad industrial buildings from non-cyclonic regions of Australia. They concluded that damage susceptibility is doubled when roller doors or other large openings fail prematurely. As can be found in literature, significant contributions in understanding the windstorm vulnerability of building stocks exist in the world. The existing literature highlights that wind forces may cause detrimental effects on residential buildings. However, no existing studies on the relationship between wind force and wind-induced damage have been done in the context of Indonesia.

The Indonesian National Disaster Mitigation Body (BNPB) [8] defines wind incidents as a form of high wind speed, higher than 12.5 m/s, or a windstorm that comes from a cumulonimbus cloud with a wind speed higher than 17.8 m/s, happening within a short period of time. In the Indonesian design code for a minimum load on buildings, the wind speed map of Indonesia is still under progress [9], and engineers are currently left to gather wind data from BMKG when the available data does not provide the 3-second gust wind speeds needed to obtain the maximum possible wind speed [10]. In the HB 212-2002 Design Wind Speeds for the Asian Pacific Region [11], the whole of Indonesia is assigned to Level 1, where the nominal wind speed, $V_R$, defined as a 3-second gust wind speed at 10 m height in a flat terrain, is calculated by the equation of

$$V_R = 70 - 56R^{-0.1}$$

(1)

where $R$ is the year return period. This gives a value of wind speed for a 50-year return period, $V_{50}$, of 32 m/s and the wind speed for a 500-year return period, $V_{500}$, of 40 m/s. However, this wind speed map treats the whole Indonesian region as one and assigns one wind speed for the whole country. A finer regional map that can account for detailed area induced wind is desirable.

It is also worth mentioning that wind occurrence and damages to residential or nonresidential buildings in Indonesia are not well documented. In 2001, Proctor et al. [12] documented local wind damage in Barito Ulu, Central Kalimantan, affecting the forest area and leaving them with gaps opened by the wind. Nurjani et al. [13] observed wind incidents data from 1990-2011 and shows that most wind incidents in Indonesia occur in Java Island. In 2019, Darman [14] analyzed the Indonesian wind data by using Online Analytical Processing and shows areas prone to wind incidents. However, none of the studies mentioned included the corresponding wind speed for each of the wind incidents, nor did they estimated these wind speeds. In 2011, Harsa et al. [15] used Satellite Animation and Interactive Diagnosis (SATAID) developed by Japan Meteorology Agency (JMA) to estimate flooding and wind speed, but only for specific cases in Jakarta and Yogyakarta. The effort to estimate wind speed in a large area has not yet been done.

Thus, this paper aims to investigate the relationship between wind incidents and wind-induced damage happening in Indonesia by focusing on one region, West Java. The study aims to estimate the wind speed at which wind incidents occur to investigate whether the occurrence is in accordance to the design wind speed [11], or the strong wind speed definition given by the law [8].
2. **Methodology**

To investigate the damages caused by the wind, public data from the national and regional levels were obtained, from BNPB and BPBD respectively. Then, each of the data sets was processed based on the available information obtained from them. The coordinates and time steps of wind incidents documented by BNPB were used to estimate the wind speed using the ERA 5 method, then the obtained wind speed was used to calculate the fragility curve. Using the BPBD data, both the total damage and the percentage of wind incidents that occur in different cities in West Java can be calculated, these data are then used to assess the relationship between wind incidents and wind-induced damage. The flowchart of the methodology used in this study can be seen in Figure 1. Further detail on each of the steps is given in the subsections below.

![Flowchart of the methodology used in this study.](image)

**Figure 1.** Flowchart of the methodology used in this study.
2.1. Public Data Gathering: National and Regional Data

Field data were taken from the Indonesian National Board for Disaster Management (BNPB) and the West Java Regional Board for Disaster Management (BPBD), with the details obtained as seen in Table 1.

Table 1. Data source used in the study with specifications.

| Data Source | Level            | Period     | Number of Cases in West Java | Known Variables                                      |
|-------------|------------------|------------|------------------------------|------------------------------------------------------|
| BNPB        | National         | 2011-2018  | 121                          | • Date                                                 |
|             |                  |            |                              | • Exact time                                           |
|             |                  |            |                              | • Exact location coordinate                           |
|             |                  |            |                              | • Victims                                              |
|             |                  |            |                              | • Damage (in the form of description)                  |
|             |                  |            |                              | • Estimation of loss                                   |
| BPBD        | Regional (Province) | 2015-2019 | 1378                         | • City/Area of occurrence,                            |
|             |                  |            |                              | • Year of occurrence                                   |
|             |                  |            |                              | • Damage (in the form of level of damage and type of buildings damaged) |
|             |                  |            |                              | • Estimation of Loss                                   |

The data from BNPB spans from 2011-2018, and contains incidents of wind-induced damage for the whole country; this was then filtered to obtain only the damage data for West Java. However, it must be noted that the wind-induced damage found in West Java from the BNPB data only shows incidents between 2012-2015. As for the remaining years (2011 and 2016-2018), we found no documented data at the national level, although wind-induced damages are still recorded at the regional level (BPBD). The regional level recorded many more cases of wind-induced damages, numbering 1378 cases between 2015-2019.

The known variables obtained from the national (BNPB) and regional (BPBD) level are different, most notably the exact location (with coordinate location), and exact time was only recorded at the national level, while from the regional level data, only the name of the area and the year of occurrence are documented.

All total wind-induced damage data each year from the regional level (BPBD) are given at a city or administrative area level, with West Java having a distinct 27 areas. Figure 2 shows the administrative areas of West Java. It is notable to mention that in the Indonesian administration system, areas can either be classified as City (Kota) or Regency (Kabupaten), with regencies typically being the larger area surrounding the city area with the same name. This is important to note because, in the obtained data, there can be data for the city level or regency level, and the damages records are separated, even when the areas are close to each other.
In this study, the exact location and time data from BNPB was used to estimate the wind speed during that particular accident (see 2.2 for an explanation of the methodology used for estimating wind speed), the same process cannot be done by using the data from BPBD since only the year of occurrence and name of the city or area was documented. The data of occurrence per year at each of the cities were used to see which area experiences the highest wind-induced damage.

However, another advantage of the regional data, other than its larger number, was that the damages have been classified into different damage states as seen in Table 2.

| Damage State      | Definition                                           |
|-------------------|------------------------------------------------------|
| No damage         | $D_1$ Safe                                           |
| Low damage        | $D_2$ Slightly safe, might need small repairs         |
| Moderate damage   | $D_3$ Moderately safe, needs repair and retrofitting  |
| Severe damage     | $D_4$ Slightly dangerous, need immediate repair and   |
|                   | strengthening                                        |
| Collapse          | $D_5$ Dangerous, evacuation and demolish needed       |

It is important to note that the classification of these data is not yet standardized in meaning, which means there is a possibility of bias due to different assessors. Also, another important factor to note is that the current practices of classification use Rapid Visual Screening standards as adopted from FEMA [16] developed for seismic hazards, where wind-induced damages would result in different types of damages that cannot be assessed with the same standards as seismic damage.

2.2. Wind-Induced Total Damage at each City and Regency

The total damage per city and area within West Java was calculated so that the areas hit hardest because of wind in terms of damage can be observed. The classification of damage given from the
regional data, as explained in Table 2, was used and then weighted using the multiplier factors given in Table 3.

| Damage State       | Multiplier Factor |
|--------------------|-------------------|
| No damage          | $c_1$             |
| Low damage         | $c_2$             | 0.25 |
| Moderate damage    | $c_3$             | 0.5  |
| Severe damage      | $c_4$             | 0.75 |
| Collapse           | $c_5$             | 1    |

The multiplier factors of $c_i$ were then used to calculate total damage in each city and regency, $D_{TC}$, using Equation 2:

$$D_{TC} = \sum_{j}^{n_y} \sum_{l}^{n_d} c_i D_{ijkl}, \forall k = 1, ..., n_a$$

where $c_i$ is the multiplier factor for different damage states, $D_i$, from no damage ($D_1$) to collapse ($D_5$), and $n_d$ represents the total number of damage states. $j$ represents the total damage at different years, where $Y$ is obtained from 2015-2019, and $n_y$ is the total number of years: five years. $k$ represents the different areas observed for all areas, $n_a$ (27 areas inside West Java). The obtained total damage of each city and regency, $D_{TC}$, was then used to calculate the percentage of damage in each city and regency, $D_{TC}$ (%), by dividing it with the total damage of the whole region as shown in Equation 3:

$$D_{TC}(%) = \frac{D_{TC,k}}{\sum_{k}^{n_a} D_{TC,k}} \times 100\%, \forall k = 1, ..., n_a$$

2.3. Wind Incidents as a Percentage of the Whole at Each City and Regency
The regional data obtained also gives the number of incidents per city and regency in West Java. However, the size of the incidents is unknown, so each incident is weighted the same. Still, these incidents were then summed for the total known years to calculate the total incidents at each city or regency, $W_C$, as calculated in Equation 4:

$$W_C = \sum_{j}^{n_y} D_{jk}, \forall k = 1, ..., n_a$$

where $j$ represents the total incidents at different years, where $Y$ is obtained from 2015-2019, and $n_y$ is the total number of years (five years), and $k$ represents the different areas observed for all areas, $n_a$ (27 areas inside West Java). The obtained total incidents in each city and regency, $W_C$, was then used to calculate the percentage of incidents in each city and regency, $W_C(%)$, by dividing it with the total damage of the whole region as shown in Equation 5.

$$W_C(%) = \frac{W_{C,k}}{\sum_{k}^{n_a} W_{C,k}} \times 100\%, \forall k = 1, ..., n_a$$
2.4. Wind Gust Data Estimated from ERA5 Reanalysis

Damages caused by wind are often related to wind gusts. Wind gusts are sudden increases in wind speed. Wind gusts are common in storms and can be very hazardous for the affected area. Wind gusts intermittently occur in very short periods. World Meteorological Organization (WMO) states that gusts should be measured by 3-second wind speed observation [17]. In Indonesia, however, such observations are rare as the conventional meteorological station does not provide wind gust reports. Instead, the available operational wind observation is mean wind data, which was obtained from a 1-hour wind speed average. The hourly wind data is less appropriate to study wind damage since no gust information was recorded.

Because no promising observations are available in the study area, we utilized estimated wind gust data from ERA5. ERA5 is one of the atmospheric reanalyses developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) [18]. The reanalysis provides a 3D global atmospheric dataset that is constructed from assimilating numerous observations into the state-of-the-art global weather models. One of the ERA5 products is a wind gust, which is deduced from surface stress, surface friction, wind shear, and atmospheric stability. Minola et al. [19] showed that the estimated wind gust from ERA5 is generally accurate and better than its predecessor, the ERA Interim reanalysis, although there are some discrepancies with observation over complex topography. Wind gusts for the 121 wind incidents were obtained by extracting the estimated gusts at the given exact geographical locations and local time.

2.5. Fragility Curve

Fragility curves are a statistical tool representing the probability of exceeding a given damage state. In this study, in order to create the fragility curve, first, the maximum estimated gust wind speed from the 121 wind incident cases stated earlier in 2.2 were sorted from lowest to largest, and the probability of damage [20] occurring for each wind speed was calculated using Equation 6:

\[
F(D_i) = \frac{r_i}{n_k + 1}, i = 1, ..., n_k
\]

where \(F(D_i)\) represents the probability of damage, \(D_i\), occurring for each maximum gust wind estimated. \(r_i\) denotes the rank among the \(n_k\), which represents maximum gust value estimates. One of the limitations of this study, however, is that we cannot obtain this curve for different damage states, for the information on the level of damage at each incident was not well-documented.

3. Results and Discussion

3.1. Wind Disaster Incidents in West Java

Only data from the regional level was used to calculate the total wind incidents in West Java between 2015-2019. It is, however, important to note that the difference between the data obtained from the national level and the regional level is significant. Only 11% of the wind incidents data for West Java was recorded on a national level. The loss of data is due to the differences in the method of documentation, which means only data with the most information is submitted to the national level. This, however, leaves 89% of incidents without proper documentation at the national level.

Figure 3(a) shows the total incidents in different areas in West Java. The area with the most number of incidents is Kab. Bogor, followed by Kota Bogor, Kab. Sukabumi, Kota Tasikmalaya, Kabupaten Ciamis, Pangandaran, Kab. Kuningan, Kab. Karawang, and Kota Cimahi. However, if the data on Bogor areas (both city and regency) are combined, it already accounts for 29% of all wind incidents in West Java documented between 2015-2019. Meanwhile, the combination of data from the 5 areas with
the most incidents (Kab. Bogor, Kota Bogor Kab. Sukabumi, Kota Tasikmalaya, and Kab. Ciamis) account for 52% of all wind incidents in West Java documented, as can be seen from Figure 3(b).

Figure 3. (a) Ranking of the 10 areas most prone to wind disasters in West Java. (b) Wind disaster incidents as a percentage of total in West Java between 2015-2019

3.2. Wind-Induced Damage in West Java

Figure 4(a) shows the total damage in different areas of West Java calculated with the multiplier factors in Table 3 and Equation 2. The area with the biggest damage is Kab. Bogor, followed by Kab. Karawang, Kab. Sukabumi, Kota Banjar, Kabupaten Ciamis, Pangandaran, Kabupaten Bandung Barat, Kab. Bandung, Kabupaten Cirebon, and Kota Bogor. The five most damaged areas, when combined, account for 57% of all damages in West Java, as can be seen in Figure 4(b).
Figure 4. (a) Ranking of the 10 areas most prone to Wind-Induced Damages in West Java. (b) Wind-induced damages as a percentage of total in West Java between 2015-2019

3.3. The Relationship between Wind Incidents and Wind-Induced Damage

It is interesting to note that the most affected areas based on numbers of incidents and number of damage induced are different (compare Figure 3(a) and 4(a)), showing that the likelihood of high wind incidents in a particular area does not necessarily translate to more wind-induced damages.

Figure 5 shows all areas plotted by its share of wind incidents and wind-induced damage between 2015-2019. The solid line represents when the share of incidents is equal to the share of wind-induced damage. The further up the city/area is positioned, the more damages it experiences in comparison to its recorded incidents, while the further right from this line a city/area is positioned, the less share of wind-induced damage it experiences in comparison to its wind incidents.

Kab. Karawang and Kota Banjar are an example of the former, with only 3% and 1% incidents recorded respectively. They experienced 16% and 8% of all wind-induced damages respectively. Meanwhile, for Kota Bogor and Kota Tasikmalaya, the opposite is true: these areas record higher wind incidents at 14% and 7% respectively, but experienced less wind-induced damages, with 3% and 3% respectively.

There are several possible scenarios of why this can happen. The first reason is that the areas with higher damages might have experienced higher wind speed. The wind incidents recorded from the regional data (BPBD) are all considered equal, because the wind speed data at the time is unavailable or not recorded. Also, given the limitation of the data that does not include the exact location or timestamp of the incident, it is difficult to investigate the wind speed independently. It would be desirable to see through deeper wind analysis of these areas to see if this is, in fact, true.

The second reason might be because of the difference in the areas’ buildings’ quality. This can especially be observed for the case of Kota Bogor and Kota Tasikmalaya, which both have higher incidents but smaller wind-induced damages. It is possible that the quality of the buildings within the cities is simply better.
However, with the currently available data, it is difficult to answer which of these reasons is truly the cause. More investigation is needed.

![Figure 5. Percentage of Wind Incidents compared to the percentage of damage.](image)

3.4. *Estimated Wind Speeds*

Figure 6 shows the calculated wind speed during the recorded time of wind incidents. The range of the wind speed is between 1.4 m/s to 13.6 m/s. As mentioned earlier, based on the definition by the Indonesian National Disaster Mitigation Body, what is considered as a wind disaster is if the wind speed is either above 12.5 m/s or 17.8 m/s (within a short period of time). When the results of the estimated gust wind speed are compared with this definition, a majority of the incidents actually happen below the given high wind speed definition. This means that the hazard was recorded because wind-induced damage occurred, yet the wind speed is not necessarily at a level that should have resulted in damage. In fact, when calculated, only 2% of the recorded data happened during a wind speed above 12.5 m/s as defined by the Indonesian Disaster Mitigation Body.

Furthermore, if compared with the design wind speed given by HB 212-2002-The Australian Standard for Design Wind Speeds for the Asia Pacific Region, which calculated a 50-year return period wind speed, $V_{50}$, of 32.1 m/s and 500-year return period wind speed, $V_{500}$, of 39.9 m/s, these wind speeds are much lower. By using Equation 2, the return period for the occurrence of the obtained range of estimated wind speed of 1.4 m/s - 13.6 m/s is between 0.13 years (1.5 months) and 0.9 years (11 months), meaning that the occurrences of these wind speeds are frequent, and therefore ideally should not result in damages. The Indonesian Design code [9] itself requires buildings to be designed for a return period of 50 years and 100 years (with a probability of occurrence of 2%).

It is clear that a wind map of the possible wind speeds for each area is needed.
3.5. **Fragility Curve**

Figure 7 shows the probability of damage occurring for each wind speed, based on the 121 cases in West Java from 2011-2018. It can be seen from this figure that even with a wind speed as low as 5 m/s, the probability of damage is 50%, while at 8 m/s, there is a 90% probability of damage. It is worth noting, however, that due to the limitation of this data, we cannot conclude the probability of the level of damage occurring for each wind speed. The data can only show that damage occurs, not the size of the damage.
4. Conclusion

This paper explores wind incidents and their corresponding wind damage in West Java. The percentage of wind incidents and total damage of every city and regency in West Java was calculated. It was found that although the relationship between wind incidents and wind-induced damage is mostly linear, there are outliers. Some outliers have more wind incidents than wind-induced damage as a percentage of the total (such as in Kota Tasikmalaya and Kota Bogor), while some outliers have fewer wind incidents but have more wind-induced damage (such as in Kota Banjar and Karawang). The true reason of why these outliers exist is difficult to conclude, but two possibilities exist: 1) that areas with lower wind incidents but more wind-induced damage have higher wind speeds and vice versa, or 2) that the areas with lower wind-induced damage but higher wind incident have better building quality. Further investigation of the reason for this non-linearity between wind incidents and wind-induced damage is needed.

The existing coordinates and timestamp of the wind incidents obtained from BNPB were used to estimate the wind speed. This is done to clarify whether the wind conditions that resulted in these incidents were indeed severe; whether they were above the Design Wind Speed given by HB 212-2002 [11], or above the definition given by the law [8]. The wind speed gust was estimated from ERA5 reanalysis hourly data. The analysis of 121 cases between 2011-2018 show that no gust wind speed that resulted in the damages were above the expected wind speed return period, $V_{50}$, of 32.1 m/s and $V_{99}$ of 39.9 m/s [11], and only 2% of the wind speeds were above the strong wind definition of 12.5 m/s given by the law [8].

The fragility curve of the data shows that even at a wind speed of only 5 m/s and 8 m/s, the probability of damage is at 50% and 90% respectively; these wind speeds are far below the standard of high wind speed from the Indonesian National Board of Disasters.

This study shows that ERA5 provides a possibility for developing a wind risk map in Indonesia. However, it should be noted that the wind data may contain some biases due to approximation in the weather model of ERA5. To date, no evaluation study of ERA5 wind gust has been carried out in Indonesia, although, in other regions, a few studies have shown good agreement between the simulated gust and observation [19]. A proper evaluation with observed wind gust in Indonesia will enable us to empirically reduce the biases, thus leading to improvements in the quality of the wind map.

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Acknowledgments
This research was done with the help of the P3MI-ITB (ITB Research, Community Service, and Innovation Program) Grant Scheme 2017-2019 from ITB. The data were obtained from the Indonesian National Board for Disaster Management (BNPB) and the West Java Regional Board for Disaster Management (BPBD West Java).