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Geospatial study for wind analysis and design codes for wind loading: A review

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ABSTRACT

Transmission line is one of the crucial components in power networking system for a Nation. Breakdown of the line caused by the structure failure absolutely will disrupt the power networking system. In order to avoid any irregularities, the factor that will contribute to the structural failure should be determined and analysed. Wind load is one of the factors that are taken into account by the design code in load design calculation of transmission tower. This paper presents study on geospatial analysis in analysing wind data and application of design codes used to calculate wind load imposed to structure. Previous study has been reviewed to understand what have been implemented by previous researcher on the application of Geospatial Analysis to the wind data. It is found that Geospatial Analysis have been applied to analyse the wind data by considering a few factors such as elevation, topography factor, terrain roughness factor and others. The design codes such as MS 1553 Malaysian Standard, EN 503411 CENELEC and ASCE 74 as well have been studied in order to understand the calculation of wind load on the structure design.

1. Introduction

Malaysia is located at the equatorial region of the earth which faces different types of monsoon season throughout the year. According to Malaysian Meteorology Department, monsoon seasons are typically affected by the changes of wind flow patterns. In Malaysia, the seasons can be categorized as northeast monsoon, southwest monsoon and inter-monsoon seasons. The northeast monsoon usually occurs on early November until March which brings steady wind of 10 to 30 knot prevails. It also known as wet season as the monsoon can cause flooding. Southwest monsoon usually commences on latter half of May or early June until September. The wind flow is generally light below 15 knots and relatively known as dry season except for Sabah. Besides the two monsoons, inter-monsoon is when the wind is typically light and variable and it happens starting on late March until early May and October until mid of November. However, thunderstorm activity is higher during the inter-monsoon periods. During this season, the equatorial line trough lies over Malaysia (Malaysian Meteorology Department).

Stathopoulos and Baniotopoulos (2007) stated in their book that frictional effects play a significant role for winds near ground surface. Ground obstructions retard the movement of air close to the ground surface, causing a reduction in wind speed. MS 1553 defined ground obstruction as natural or man-made objects which caused turbulent wind flow, such as tree, building, and others (MS, 2002). However, at certain height above the ground, the ground obstruction is no longer give effect to the movement of air which the height is call gradient height (function of ground roughness) (Stathopoulos and Baniotopoulos, 2007). In addition to that, the roughness of terrain contributes a major influence on the wind. Roughness of the ground reduced the mean wind velocity but at the same time, the wind becomes turbulent and hard to describe. Mean wind velocity increases with the height above the ground. The different of terrain environment effects can be categorized according to their associated roughness length (Din, 2012). Mendis et al. (2007) stated in their study that terrains can be categorized based on the roughness length. The wind speed varies at the surface from almost zero to the gradient wind speed at certain height called gradient height in the boundary layer and the thickness of boundary layer is depends on the type of terrains. Gradient wind

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speed is the wind speed at upper level where air movement is driven by pressure gradients and the fractional effect is imperceptible. Fig. 1 shows the mean wind profile for different terrains. The gradient height of open sea is much lower than the gradient height of city centre which indicates that the roughness length of the open sea is lower than the others (Mendis et al., 2007).

Issue on structural damage due to environmental factor such as thunderstorm, flood, landslide and others becoming increasing nowadays. Based on a report by Majid et al. (2012) on wind related disaster and wind environmental issue for years of 2012, there are numbers of damage cases occurred which are related to wind has been recorded in Malaysia due to lack of concern regarding the effect of wind towards building structure. Fig. 2 shows the statistic of damage due to wind storm for peninsular Malaysia from January 2009 until June 2012 (Majid et al., 2012).

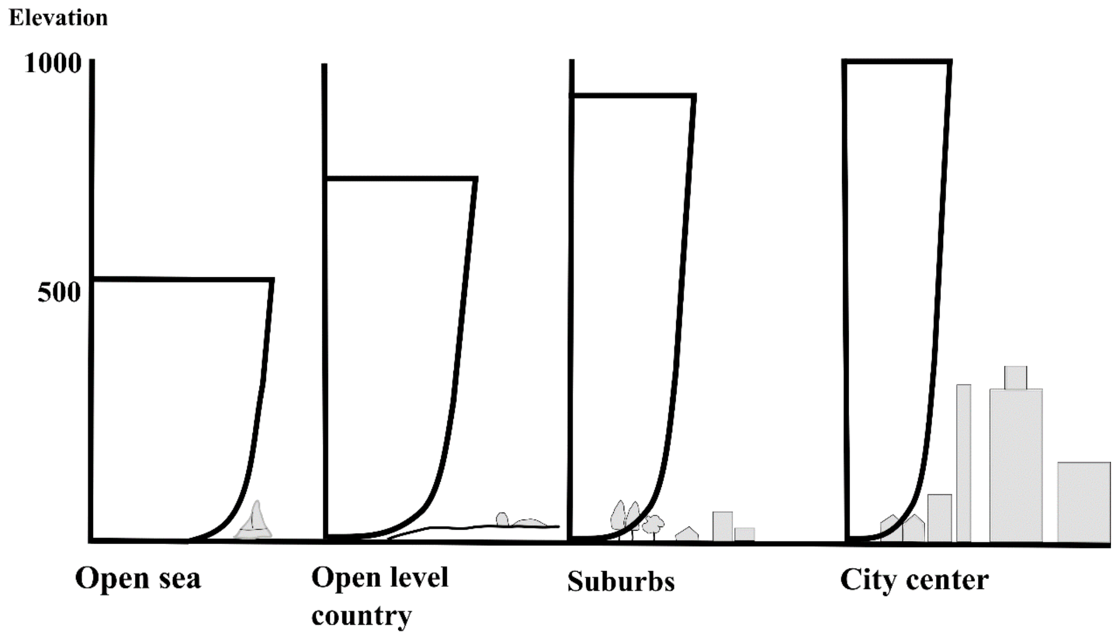

Fig. 1: Mean wind profiles for different terrains (Mendis et al., 2007)

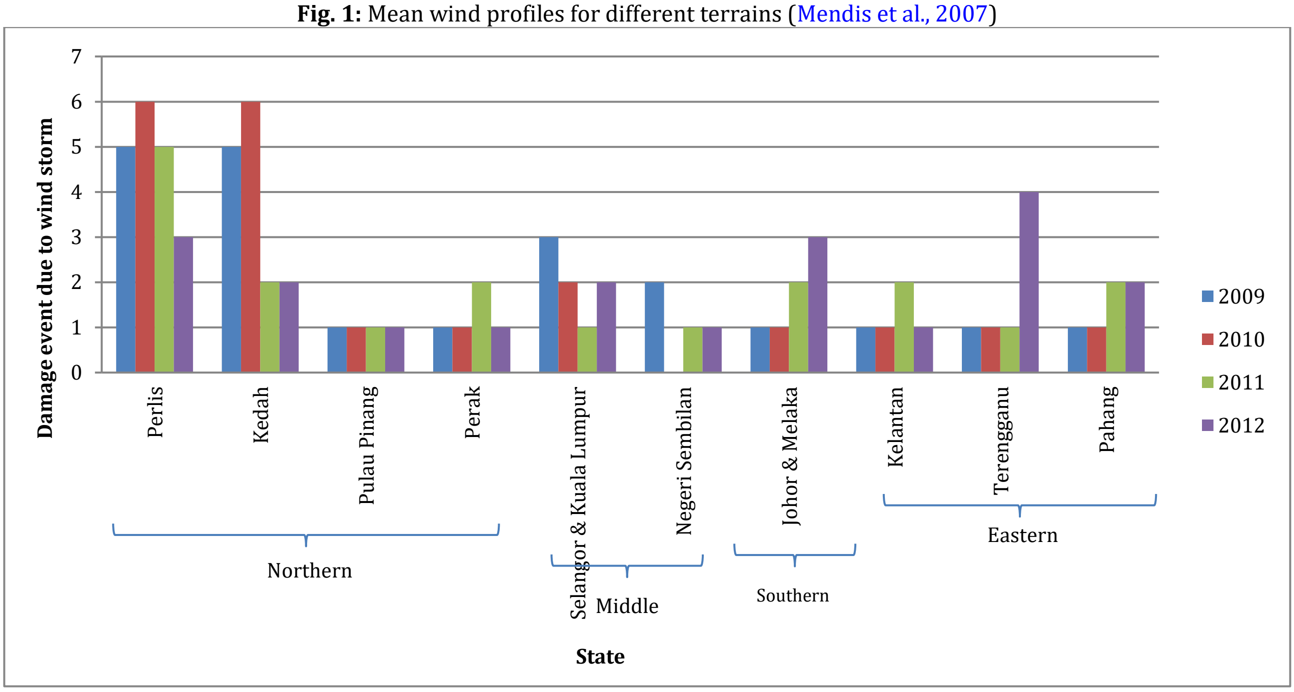

Fig. 2: Statistic of damage due to wind storm for Peninsular Malaysia on Jan 2009-June 2012 (Majid et al., 2012)

Recently on April 2017, New Straits Times have been reported that 50 houses in 10 villages are badly destroyed by evening thunderstorm in Alor Setar, Kedah and no injuries reported in the case. However, most of the houses were blown away by the strong thunderstorm. Another case reported by the New Straits Times on 2016 that a gusty wind strikes Seremban which caused some parts of the ceiling at D'S2 Mall PKNS Complex building collapsed. The cases that happened might be because of lack of concern on wind effect towards building structure besides the age factor of the building. Thus, wind speed estimation is very important in the structural design of any building. MS 1553, Code of Practice on Wind Loading for Building Structure is one of the codes that discussed on the basic wind speed in

Peninsular Malaysia that can be a guide in estimating wind load. Fig. 3 shows the modified figure of basic wind speed throughout Peninsular Malaysia based on zones. Zone I is presented by the inland region and having basic wind speed 33.5 m/s. While Zone II is presented by the shoreline region and having basic wind speed 32.5 m/s (MS, 2002).

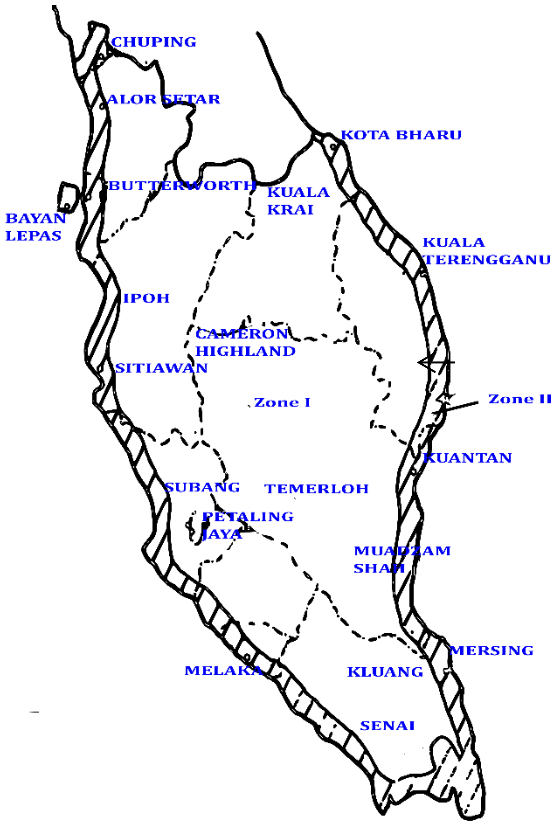

Fig. 3: Basic wind speed throughout Peninsular Malaysia based on zones (MS, 2002)

According to the Integrated Annual Report of TNB (2016), the maximum demand of electricity in Malaysia was recorded on April 2016 which was 17,788 megawatts through 22,478 kilometers of transmission network. The demand are from all sectors includes industrial, commercial, residential and others (TNB, 2016). Failure of transmission line definitely will affect the national economy and people life due to power disruptions. There are a few factors that can contribute to the power supply interruption including the natural disasters (i.e., wind, storm, flood, landslide, others) which give the percentage of 5.77% on the year of 2014. Besides natural disasters, quality of materials, damage done by third party, overload and faulty equipment also are the factors which reported to be the causes of power supply interruption in Malaysia for 2014 (EC, 2014). Tian et al. (2014) summarized a few cases reported on failure of transmission tower caused by strong wind in the province of China. In 2007, many transmission towers damaged seriously because of the strong wind in Liaoning. While in 2010, strong wind and rain in Guangdong caused five transmission towers to collapse and last but not least in 2013, typhoon Fitow that stroked Zhejiang had caused many transmission towers collapsed and destroyed the power facilities (Tian et al., 2014). Fig. 4 shows the transmission tower failure caused by storm that occurred at regional South Australia.

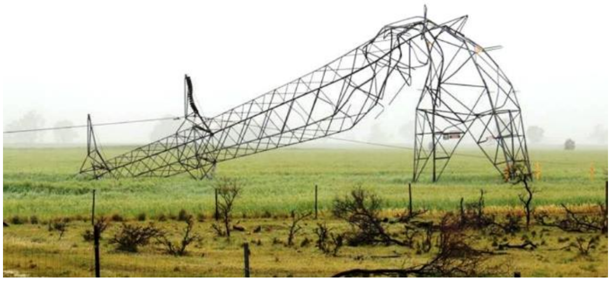

Fig. 4: The picture of the failure of transmission tower under wind excitation (Tian et al., 2014)

In other words, wind study is a significant effort that needs to be done in fulfilling the need of structural design, especially for high rise building or transmission tower. By the help of geospatial analysis on the obtained data from available wind station, the pattern of wind direction and wind velocity can be clearly seen throughout the study area. Besides, geospatial analysis is done to classify a few geospatial parameters such as terrain condition, altitude, wind potential and others in order to relate with the effect of wind velocity on the area. Wind velocity will affect the wind load that imposed to the structural building based on the design calculation provided in design codes. Wind data on available wind stations for Peninsular Malaysia can be obtained from Malaysian Meteorology Department, MMD in the basis of hourly, daily, weekly or monthly every year. There are about 276 MMD wind stations available throughout Peninsular Malaysia. This paper presents study of geospatial analysis in analysing wind data and application of design codes used for wind load design.

2. Overview on geospatial analysis

Geospatial analysis is an approach which using statistical analysis on the data that have geographical aspect on it. There are many application of geospatial analysis such as climate change modelling, weather monitoring, human population forecasting as well as to describe the pattern of wind velocity and wind direction at particular area. Geographical Information System, GIS is a platform which contains geospatial analysis tool in it. In past few decades, GIS have been extensively used to help in finding suitable location for development of wind farm. The GIS have the function to integrate the large spectrum of geospatial information in order to decide for wind energy development (Miller and Li, 2014). Based on the book titled Geospatial Analysis: Breaking Down What You Need to Know, the author stated that, understanding spatial data is significant in doing geospatial analysis. Spatial data is geographic and represented as features. A feature is said to be a static object on map such as river, building or street. Ye (2013) mentioned in his report that there are 2 categories of spatial interpolation which are deterministic method and geostatistical method. Deterministic method refers to the prediction from the measured values based on the degree of smoothing and similarity without considering uncertainty. While geostatistical method considers randomness in the interpolation and use statistics of the measured values. Generally the geostatistical methods used are kriging and co-kriging.

Wind energy development as well applied the use of geospatial analysis for the purpose of wind potential determination at a particular places (Ye, 2013; Schlichting, 2009; Ibrahim et al., 2015; Masseran et al., 2012). In a study conducted by Ibrahim et al. (2015) to analyse the wind potential for Malaysia, spatial wind modelling was developed first in order to simulate the spatial wind data. From the hourly wind map, spatial wind power density is then computed by using the spatio-temporal analysis. Lastly, the wind power density spatial distribution for whole Malaysia was obtained in a histogram by spatial analysis (Ibrahim et al., 2015). Fig. 5 shows the spatial distribution for the map of mean wind speed in Peninsular Malaysia (Masseran et al., 2012). The values of mean wind speed are interpolated throughout Peninsular Malaysia.

A standard is used to categorize the value of wind speed and wind power density that is suitable for wind turbine development. Table 1 shows the wind power classified from 1 to 7 which represents the power density of wind and speed of wind at 30m and 50m heights above the ground. According to the standard, areas which fall into class 4 or greater are considered relevant for most wind turbine development. Areas which consider being in Class 3 are relevant for wind energy development if tall towers are implemented. While, areas in Class 2 are marginal and areas in Class 1 are not relevant for wind energy development (NREL, 1997).

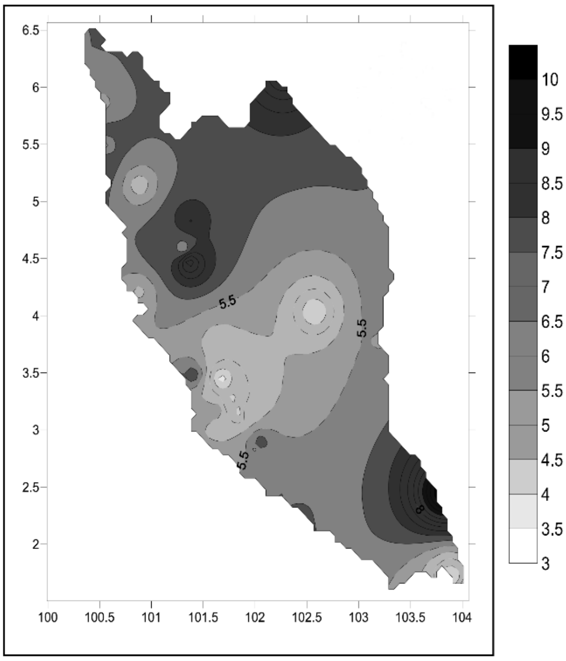

Fig. 5: The spatial distribution of mean wind speed in Peninsular Malaysia (Masseran et al., 2012)

Table 1: Classes of wind power density (NREL, 1997)

Wind Power Class	30m		50m	
	Wind Power Density (W/m^2)	Wind Speed (m/s)	Wind Power Density (W/m^2)	Wind Speed (m/s)
1	≤ 160	≤ 5.1	≤ 200	≤ 5.6
2	≤ 240	≤ 5.9	≤ 300	≤ 6.4
3	≤ 320	≤ 6.5	≤ 400	≤ 7.0
4	≤ 400	≤ 7.0	≤ 500	≤ 7.5
5	≤ 480	≤ 7.4	≤ 600	≤ 8.0
6	≤ 640	≤ 8.2	≤ 800	≤ 8.8
7	≤ 1600	≤ 11.0	≤ 2000	≤ 11.0

Ellison and Rutz (2015) in their study on the effect of surface roughness in wind speed by the application of, GIS mentioned that the spatial topographic data that obtained from variety sources such as surface survey can be merged with the attribute data obtained from the country database. The system used to do mapping on surface roughness surrounding the study area. The significant geographical mapping data that collected by the study includes roads, land use, topography and buildings (Ellison and Ruts, 2015). It can be done by the help of geospatial analysis that already embedded in the GIS as well as the other function in it.

Besides the applications that have been mentioned above, Geospatial Analysis can be implemented to develop a land hazard transmission tower map. The map is used to enhance the understanding of the possible failure that might occur on a transmission tower due to wind excitation. The map can show the prone area which subject to strong wind over the year as well. In other words, Geospatial Analysis is a useful method not only in developing a new development but to maintain and evaluate the condition of current assets as well.

3. Overview on wind load design codes

Transmission tower is considered as the structure that is sensitive towards wind and wind load is the main control of load case on the structure. Based on previous cases, there were many accidents occurred on transmission tower caused by strong wind including damage and collapse of the tower. Thus, wind load is very important parameter that needs to be considered in the structural design of the transmission tower. The calculation values and methods for the wind loads are fundamental for the transmission tower structure design. According to study by Naidu, analysis on wind static is conducted by referring to IS-875 (Part-3) code. The design wind speed is calculated by corresponding to wind consideration and then wind pressure which corresponding to the design wind speed is calculated. As final result, the wind load is obtained. The design wind speed as stated by Naidu, considered a few factors which are terrain condition, height of the structure and topographic factor (Krishna and Naidu, 2016).

In order to determine the wind action for structure design, there are a few wind parameters that need to be considered in MS (2002). There is site wind speed, design wind speed from site wind speed, design wind pressure and distributed forces as well as wind action. The design code covers structures within the criteria of buildings with less than 200m high, structures with roof span less than 100m and structures other than offshore structures, bridges and transmission lines. Site wind speed in MS (2002) is calculated by using the equation below:

$$V_{sit} = V_s (M_d)(M_{z,cat})(M_s)(M_h) \quad (1)$$

where,
V_s=33.5m/s zone 1 and 32.5m/s zone 2
M_d=1
$M_{z,cat}$=terrain/height multiplier
M_h=hill shape multiplier
M_s=shielding multiplier

Terrain category in this code refers as follow:

a) Category 1: Exposed open terrain with few or no obstruction
b) Category 2: Water surfaces, open terrain, grassland with few well scattered obstruction having height generally from1.5m to 10m
c) Category 3: Terrain with numerous closely spaced obstruction 3m to 5m high such as areas of suburban housing.
d) Category 4: Terrain with numerous large and closely spaced obstructions such as large city centres and well-developed industrial complex.

The maximum of site wind speed multiplied by importance factor, I which consider the category of structure is taken as building design wind speed V_{des}. Next is the design wind pressure, p on structure:

$$p = \left(0.5_{\rho_{air}}\right) [V_{des}]^2 C_{fig}\, C_{dyn} \quad (2)$$

where,
ρ_{air} =Density of air (1.2kg/m^3)
C_{fig}=Aerodynamic shape factor
C_{dyn} =Dynamic response factor which taken as 1 unless the structure is wind sensitive

Wind action in this code is discussed by taking into account a few aspects such as directions to be considered. Each designed structures must be capable to withstand the wind forces derived by considering the action from less than four critical orthogonal directions aligned to the structure (MS, 2002). The natural wind normally has an incidence angle which follows the direction of transmission lines. For the purpose of design, the wind loads of transmission towers consist of transversal direction and the longitudinal direction of transmission lines. The method of calculation of the wind loads under skewed wind loading for transmission towers needs to be studied, as it plays an important role in the structural design of the towers (Yang et al., 2015). Besides that, forces on building elements as well affect the wind action. The forces, F on building elements such as wall, roof and others must be calculated from the pressures applied to the assumed areas. For enclosed building, internal pressures must be considered to act simultaneously with external pressures because the most severe combination will be choosing in the design. Last but not least, the aspect that is considered in wind action discussed in the code is the forces and moment of complete structure. The total resultant forces and overturning moments of the complete structure are include as summation of the effects of the external pressures on all surfaces of the building.

There are two types of load carried by transmission tower that have been categorized by European Standard, EN50341-1 which are permanent load and wind load. Permanent load consists of self-weight of support, insulator set and conductor resulting from the adjacent spans. While for wind load, terrain factor is the main consideration while doing the calculation in the code. The gust wind speed is critical for overhead line design in the ultimate state. Wind speed is calculated based on a few factor such as turbulence, terrain category and gust factor. Turbulence is observed as variation time wise and space wise of the momentary value of the speed about its mean value. The turbulence intensity is dependent on the terrain and the terrain is divided into four categories. There are relation between gust wind speed and mean wind speed which controlled by the gust factor k_g as follows:

$$V_g = k_g . V_{mean} \quad (3)$$
$$k_g = 1 + \frac{2.28}{ln\frac{h}{z_0}} \quad (4)$$

In this standard, it is optional to practice the mean wind speed Vmean or the gust wind speed Vg as a base for the strong wind speed in accordance with the practice within each country. In countries where the mean wind speed option is used, the reference wind speed V_R at site is evaluated from the reference wind speed at nearby measuring site of category II by using the equation below. Reference wind speed is the wind speed taken into account 10m above the ground at the site. The value of k_T and z_0 is depends on the terrain category as in Table 2.

$$V_R = k_T . ln\frac{10}{z_0} . V_R(II) \quad (5)$$

If the gust wind speed is used, it is the best to take the reference wind speed at nearby site without considering the terrain category. For overhead line elements up to 10m above ground, the reference wind speed is used directly:

$$V_h = V_R \tag{6}$$

While for overhead line element more than 10m above the ground, the reference wind speed is calculated using below equation:

$$V_h = \frac{ln\frac{h}{z_0}}{ln\frac{10}{z_0}} . V_R = k_T . ln\frac{h}{z_0} . V_R(II) \tag{7}$$

where,
V_h=Wind speed at arbitrary height above ground
h=Height above ground
k_T =Terrain factor
z_0=Ground roughness parameter

In a case study at a region in Korea done by Maharani et al. (2009) found that in general, wind speed is increasing when it blows up to the windward slope of a hill or a ridge. The maximum increasing of wind speed is usually at near the crest (Maharani et al., 2009).

Table 2: Terrain factor and ground roughness parameter for different terrain categories

Terrain category	Characteristics of the terrain	k_T	z_0
I	Rough open sea, lakes with at least 5km fetch upwind and smooth flat county without obstacles.	0.17	0.01
II	Farmland wind boundary hedges, occasional small farm structures, houses or trees	0.19	0.05
III	Suburban or industrial areas and permanent forests	0.22	0.30
IV	Urban areas in which at least 15% of the surface is covered with buildings with mean height>15m	0.24	1.0
V	Mountainous and more complex terrain where the wind may be locally strengthened to weakened.	Shall be evaluated separately, possibly by meteorologist	

While ASCE 74 mentioned that load on transmission tower are the forces that applied on the wires and on the structure. The load applied on the wires are then transfer to the structure and the loads should include relevant load factors. The code recommends the minimum loads value for installing ground wires and conductors (ASCE, 2009):

1. Transverse and vertical loads - use a 0.144-kPa wind (35 mph, 15.6 m/s). No ice on the wires and structure. Use the lowest temperature that can be expected to occur during stringing operations.
2. Transverse wind loads - use the maximum design wind span with a load factor of 1.5.
3. Transverse and longitudinal components of wire tension – use tensions based on initial wire conditions at the lowest temperature that can be expected to occur during stringing operations with a load factor of 1.5.
4. Vertical loads, use the higher of the following conditions:

a. For dead-end conditions with pulling or tensioning equipment at ground level, use the vertical component of the pulling line, the maximum single vertical span, and a load factor of 1.5. If the pulling line slope is not known, use a 3/1 ratio (horizontal/vertical).
b. For intact conditions (ahead and back spans are attached to the structure), use the maximum design low-point distance and a load factor of 2.0.

Same goes to EN 50341-1, ASCE 74 also give the standard to calculate wind load for overhead transmission line. The wind force can be determined by using the equation below:

$$F = \gamma_W Q K_z K_{zt} (V_{50})^2 G C_f A \tag{8}$$

where,
F=Wind force in the direction of wind
γ_w=load factor to adjust F to the desired return period
Q=numerical constant
K_z=velocity pressure exposure coefficient which modifies the basic wind speed for various heights above ground.
K_{zt}=topographic factor
V_{50}=basic wind speed, 50-year return period, 3 sec gust at 10m above the ground in flat and open country terrain
G=gust response factor for conductors, ground wires and structures
C_f=force coefficient values
A=projected area on a plane normal to the wind direction

Ground roughness in this code is grouped by different type of exposure categories:

Exposure B=Classified as urban and suburban area, well wooded area, area with numerous, closely spaced obstructions with accommodate single family residence or more.
Exposure C=Classified as open terrain with scattered obstructions with height generally less than 9.1m. Flat, open country, farms, grassland, and shoreline in hurricane-prone regions as well include in this category.
Exposure D=Classified as flat, unobstructed area which directly exposed to wind. Applied to structures which directly exposed to water bodies and coastal beaches.

ASCE 74 differentiates between gust factor and gust response factor. Gust factor is the ratio of the gust wind speed at a specified short duration to some mean wind speed measured over specified averaging time. While gust response factor is the ratio of peak load effect on structure or wire to the mean load effect corresponding to the design wind speed. In other words, gust factor is the multiplier of mean wind speed to get the gust wind speed and gust response factor is the multiplier of design wind load to get the peak load effect. The gust response factor has to be determined separately for wire and structure (ASCE, 2009).

Topographical factors that affect the wind speed over the transmission line are funnelling of wind, mountains and hills as well as canyons and valleys. Funnelling of wind occur when the air flow from unrestricted area to restricted area. Venturi effects that occur cause the air to accelerate as it funnelled into the canyons. Typically the wind is called as local canyon wind. The design load should be adjusted accordingly as the wind velocity in the canyons maybe double from the wind at the unrestricted areas on each side. The other case that might increase the wind speed is when the wind is blowing to a ridge of mountain. The compressed air will release and accelerate on the leeward side with the effect of combination between temperature and pressure (ASCE, 2009).

4. Conclusion

From the study, it is found that Geospatial analysis can be used to analyse wind data by considering a few parameters involve in wind analysis such as terrain condition, altitude of study area, as well as the pattern of wind velocity and wind speed stroked the study area. Geospatial analysis could be supporting information on the wind design calculation provided in the design codes. Generally, the design codes used for wind load design include MS 1553 Malaysian Standard, EN 503411 CENELEC and ASCE 74. MS 1553 explained in the code on the wind load design requirement for building structure not specifically for transmission line. While both EN503411 and ASCE 74 explained on wind load design requirement for transmission line. However, all the codes highlighted the same parameters which affect the wind load such as topographic factor, basic wind speed and terrain factor. All the codes have different type of exposure condition categorized in each code.

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