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A strong wind prediction model for the railway operation based on the onsite measurement and the numerical simulation

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ABSTRACT: In this study, a prediction method for the strong gust was proposed, which can take the effect of not only local terrain but also meteorological conditions into account. Predicted maximum gust by this method shows good agreement with the measurement. In addition, a time series based method for the prediction of the frequency of strong wind in a control section was proposed. Predicted frequency of strong wind shows good agreement with the measurement, while the conventional methods underestimate or overestimate the frequency. Finally, proposed methods were applied to the regulation of the train operation, considering wind direction and wind fence. The frequency of the regulation of the train operation at a 6km test section decreases from 0.16% to 0.11% when the wind direction is considered and further decreases to 0.08% when the wind fence is installed.

1 INTRODUCTION

Railway operators regulate train operation and install wind fences as countermeasures against the strong wind. The assessment of the strong wind along railway tracks is important for the adequate implementation of these countermeasures. Cléon et al. (2002) estimated the strong wind along railway track from measured wind speed at one site and the numerical simulation, which takes the effect of local terrain into account. Based on the estimated wind speed, they calculated the frequency of occurrence of strong wind in control sections by assuming the occurrences of the strong wind at different sub-sections are independent each other. However, the gust event is not only affected by local terrain but also by meteorological patterns. In addition, the assumption that the occurrences of the strong wind events between different sub-sections are independent is not always satisfied when the length of the sub-sections becomes short.

In this study, a prediction method for the maximum three second gust along railway track is proposed, in which the onsite measurement data at one site and mesoscale simulation nested in global analysis data are used. Then, a prediction method for the frequency of strong wind events in control section is proposed, which can consider the correlation between the strong wind events at different sub-sections. Finally, proposed methods are applied to the train regulation, considering the wind direction and the wind fence.

2 A STRONG WIIND PREDICTION METHOD BASED ON THE ONSITE MEASUREMENT AND THE NUMERICAL SIMULATION

2.1 *Prediction method of maximum three second gust*

This section explains a prediction method of the maximum three second gust, in which the effects of local terrain and the meteorological phenomena on the wind speed and the wind direction are taken into account.

The flow chart of the proposed method is shown in Figure 1. Numerical simulation by the mesoscale meteorological model, RAMS (Pielke et al., 1992) is carried out to obtain the one year time series of mean wind speed and wind direction with 1km resolution. These time series data are downscaled to the reference site where the anemometer is installed and the prediction sites where the wind speed and direction are to be estimated by the micro-scale wind prediction model, MASCOT (Ishihara et al., 2003) with the Dynamical Statistical Downscaling Approach (Yamaguchi et al., 2003). The wind speed ratio and the changes in wind direction between the reference site and the prediction sites are calculated as functions of wind direction from the simulated time series. The wind speeds at the prediction sites are estimated by multiplying the wind speed ratio to the measured wind speed at reference site. The wind directions at the prediction sites are also estimated by adding the change in wind direction to the measured wind direction at reference site. The gust factor is calculated as a function of wind direction from the estimated turbulence intensity by the microscale wind prediction model and the maximum gust is estimated by multiplying the gust factor to the time series of the predicted mean wind speed at the prediction sites.

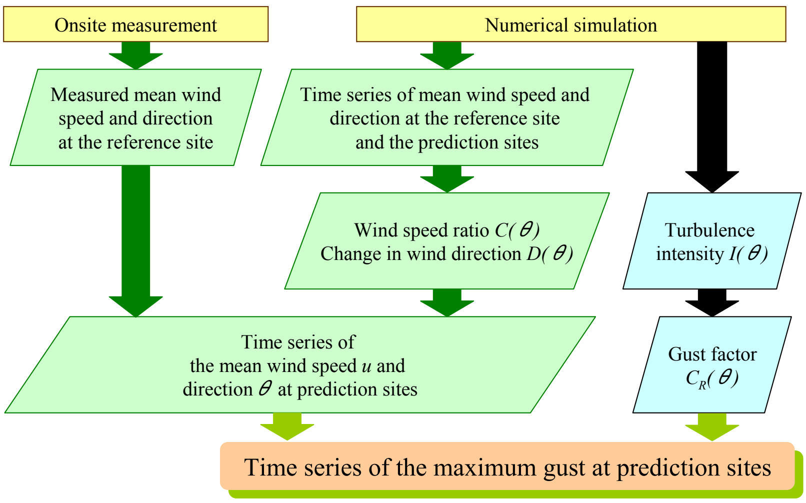


Figure 1. The flow chart of the proposed method

In this study, the wind speed ratio $C(\theta_{\mathrm{ref}}^{\mathrm{model}})$ and the change in wind direction $D(\theta_{\mathrm{ref}}^{\mathrm{model}})$ between the two sites are assumed to be functions of the wind direction $\theta_{\mathrm{ref}}^{\mathrm{model}}$ obtained by the numerical simulation. The wind speed ratio and the change in the wind direction are estimated by the least square method as shown in Equations (1) and (2).

$$C(\overline{\theta}_{ref}) = \underset{C(\theta)}{\arg\min} \sum_t \left(u_{\mathrm{ref}}^{\mathrm{model}}(t) \times C(\theta_{\mathrm{ref}}^{\mathrm{model}}) - u_{\mathrm{site}}^{\mathrm{model}}(t) \right)^2 \quad (1)$$

$$D(\overline{\theta}_{ref}) = \underset{D(\theta)}{\arg\min} \sum_t \left(\theta_{\mathrm{ref}}^{\mathrm{model}}(t) + D(\theta_{\mathrm{ref}}^{\mathrm{model}}) - \theta_{\mathrm{site}}^{\mathrm{model}}(t) \right)^2 \quad (2)$$

where $u_{\text{ref}}^{\text{model}}(t)$ and $\theta_{\text{ref}}^{\text{model}}(t)$ are the wind speed and direction at the reference site where the anemometer is installed and $u_{\text{site}}^{\text{model}}(t)$ and $\theta_{\text{site}}^{\text{model}}(t)$ are those at the prediction sites.

The one minute averaged wind speed $\bar{u}_{\text{site}}$ and the direction $\bar{\theta}_{\text{site}}$ at any point along the railway are calculated from the one minute averaged wind speed $\bar{u}_{\text{ref}}$ and the direction $\bar{\theta}_{\text{ref}}$ at the reference site, and predicted wind speed ratio $C\left(\bar{\theta}_{\text{ref}}\right)$ and the change in wind direction $D\left(\bar{\theta}_{\text{ref}}\right)$ as follows:

$$\bar{u}_{\text{site}}\left(t\right)=\bar{u}_{\text{ref}}\left(t\right)\times C\left(\bar{\theta}_{\text{ref}}\right) \tag{3}$$

$$\bar{\theta}_{\text{site}}\left(t\right)=\bar{\theta}_{\text{ref}}\left(t\right)+D\left(\bar{\theta}_{\text{ref}}\right) \tag{4}$$

The three-second maximum gust $\hat{u}_{\text{site}}\left(t\right)$ at the prediction site can be calculated by multiplying the gust factor $G_R\left(\bar{\theta}_{site}\right)$ to the predicted mean wind speed, and the gust factor can be estimated by multiplying the peak factor k_p to the turbulence intensity $I_u\left(\bar{\theta}_{site}\right)$ obtained by the microscale wind prediction model.

$$\hat{u}_{\text{site}}\left(t\right)=\bar{u}_{\text{site}}\left(t\right)\times G_R\left(\bar{\theta}_{\text{site}}\right)=\bar{u}_{\text{site}}\left(t\right)\times\left(1+k_p I_u\left(\bar{\theta}_{site}\right)\right) \tag{5}$$

In this study, the peak factor k_p is estimated by the formula proposed by Ishizaki (1983).

$$k_p=\frac{1}{2}\ln\frac{T}{t},\quad T=60\,\text{sec},\quad t=3\,\text{sec} \tag{6}$$

2.2 *Prediction of a strong wind event*

Proposed method is verified by using the field measurement data at five measurement points along a railway line as shown in Figure 2. The measurements were carried out for one year from February 2004 to January 2005. Gust wind speeds with 4Hz sampling rate were recorded, which are equivalent to one second averaged value according to three-cup anemometers. Here, the measurement site No.3 is assumed to be the reference site and the other sites are assumed to be prediction sites for the verification.

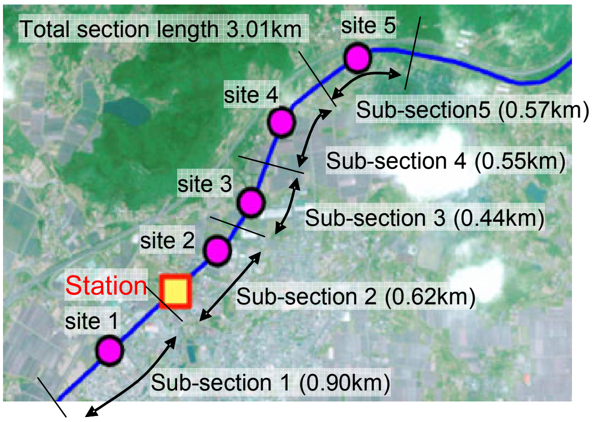
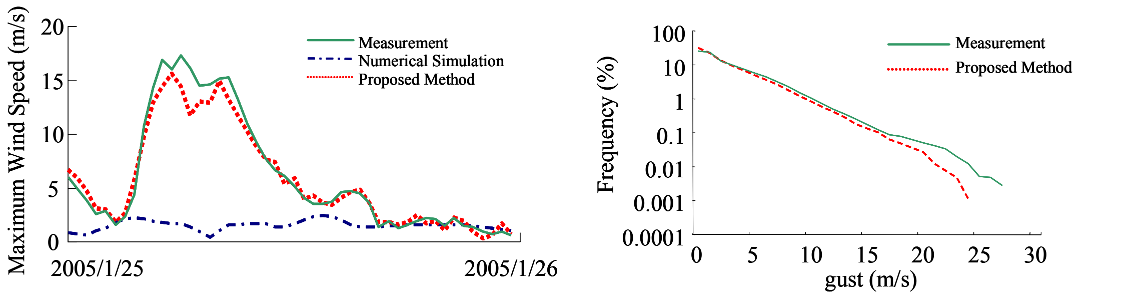


Figure 2. Five measurement sites and the virtual section and sub-sections

Figure 3 (a) shows the maximum gust at site No. 2 on 25th of January 2005. The predicted wind gust by the proposed method with the onsite measurement and the numerical simulation shows good agreement with the measurement, while that only by the numerical simulation cannot capture the strong wind event, even though the annual mean wind speed is predicted well by Dynamical Statistical Downscaling Approach. The underestimation of strong wind events is due to the limitation of the current mesoscale model for the prediction of the down slope wind, a famous local weather system in a mountainous region. Figure 3 (b) shows the annual frequency distribution of maximum gust at No.2 obtained by the measurement and by the proposed method. The proposed method slightly underestimates the frequency at wind speed more than 20m/s. The reason of this underestimation can be supposed to be the difference of the averaged time of gust, i.e., the three second averaged gust is used in the proposed method, while measurement is estimated to be the one second averaged gust.



(a) Time series of maximum wind speed in 1 minute (b) Annual frequency distribution of maximum gust

Figure 3. Comparison of the strong gust between the predicted and the measured maximum gust at site No.2

3 PREDICTION METHOD OF MAXIMUM GUST FREQUENCY IN CONTROLLED SECTION

In order to evaluate the cost performance of the countermeasures of strong wind such as installation of wind fences and train regulation, it is necessary to accurately predict the frequency of the strong wind. In this section, a time series based method to predict the frequency of strong wind is proposed and two existing methods based on probabilistic density functions are investigated by comparing with the measurement.

3.1 *Prediction method of strong wind frequency in a control section*

The simplest method for the prediction of the frequency of occurrence of strong wind in a control section is to assume that measured wind at one measurement point can represent winds in the section, that is, to assume that winds have the complete correlation in the control section for the train regulation. In this method, the frequency of the strong wind that exceeds the regulation wind speed u^{limit} can be estimated as follows:

$$P_{nk} = P\left(u_{obs} > u^{\text{limit}}\right) \quad (7)$$

where P_{nk} is the frequency of the strong wind in the control section and u_{obs} is the wind speed at measurement site. The disadvantage of this method is that strong wind events that occur at the point other than the measurement site cannot be included.

In order to account for the variations of wind speed in the control section due to the local terrain, Cléon (2002) proposed a prediction method in which the control section is divided into number of sub-sections as shown in Figure 4 and it is assumed that there is no correlation between the wind speeds in sub-sections. The frequency of the strong wind P_{nk} in the control section can be estimated as follows:

$$P_{nk} = 1 - \prod_i \left[1 - P_i(u_i > u^{\text{limit}}) \right] \tag{8}$$

where u_i is the wind speed in sub-section i and is estimated by Eq. (5), in which the observed wind speeds and directions at the measurement site are used as shown in Section 2.1. The advantage of this method is that the frequency of the strong wind P_{nk} can be calculated analytically and the variations of wind speed in the control section can be taken into account. The frequency of the strong wind assessed by this method could be overestimated if the strong winds in different sub-sections correlated each other. Since these two methods explained above are based on the probability density function of wind speeds at the site, they can be called "the Probability Density Function based Method (PDFM)".

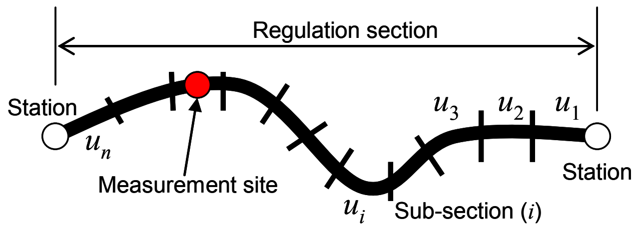


Figure 4. The regulation section and sub-sections

In order to accurately estimate the frequency of the occurrence of the strong wind, a Time Series based Method (TSM) is proposed, which can consider the correlation between the wind speeds in different sub-sections by using time series of wind speeds and directions at sub-sections. The frequency of strong wind can be estimated as follows:

$$P_{nk} = P\left(\max(u_i) > u^{\text{limit}} \right) \tag{9}$$

3.2 *Effect of the correlation of wind speeds and intervals of the sub-section*

The frequencies of the strong wind are affected by the correlation of winds as described above. A virtual section whose distance is about 3km with five sub-sections is considered as shown in Figure 2. The site No. 3 is used as the reference site and the wind speed at the other sites are estimated by using the method proposed in Section 2 and the frequency of occurrence of the strong wind event is estimated by using the three methods described above. Figure 5 (a) shows the frequency of strong wind exceeds 25m/s estimated by the three methods. The frequency of the strong wind event estimated from all the measurement data is denoted as measurement. The predicted frequency of the strong wind by the TSM shows good agreement with the measurement. On the other hand, the predicted frequency by the PDFM with complete correlation assumption is underestimated due to the ignorance of the strong wind at the sites where the anemometers are not installed and the predicted frequency by the PDFM with no correlation assumption is overestimated due to the double counting of the strong winds which correlate each other.

The interval of the sub-section also affects the predicted frequency of the strong wind. In order to investigate the effect of the interval, the frequencies of the strong wind are calculated by three methods for different intervals of the sub-sections in a test section whose distance is about 6km as shown in Figure 5 (b). The frequency estimated by the proposed method TSM is almost constant when the intervals are less than 200m and slightly decreases as the intervals increase, while the frequency predicted with no correlation assumption increases rapidly when the intervals are less than 1,000m and shows unrealistic values. In the mountainous countries such as Japan, the intervals of the sub-section have to be less than 200m and the method with no correlation assumption overestimates the frequency of the strong wind remarkably. Although the method with no correlation assumption is applicable if the local terrain is moderate and the intervals can be set long, the proposed method considering the correlation between the strong winds is applicable to the complex terrain.

In order to find an interval-independent value for the predicted frequency of strong wind by the proposed method, the predicted frequency is expressed as a function of the length of the interval as follows:

$$P_{nk} = C_1 r^{C_2} + C_3 \quad (10)$$

where r is the length of the interval and parameters C_1, C_2, C_3 are decided by using the frequencies of the strong wind obtained by proposed method as $C_1 = -3.04^{-9}$, $C_2 = 1.75$, $C_3 = 1.63^{-3}$. The interval-independent value is obtained when the interval of the sub-section approaches zero. Table 1 shows the prediction errors of the predicted frequencies by three different methods. The absolute value of the prediction errors by the proposed method are less than or equal to 2% when the length of intervals are less than 200m, while the prediction errors by the method with no correlation assumption increase rapidly and shows minimum absolute value of 18.2% when the length of intervals is equal to 1000m. The prediction errors by the method with complete correlation assumption are constant value and reach to -49.1% in the mountainous region.

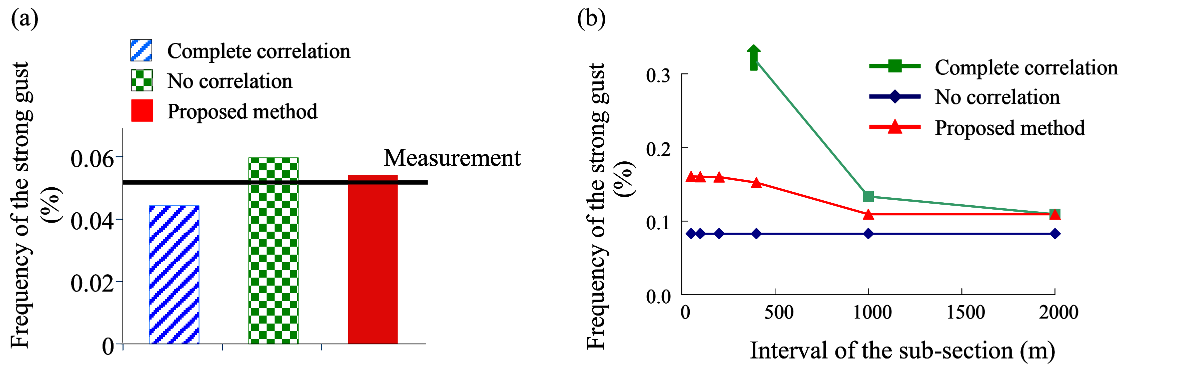


Figure 5. Frequency of strong wind over 25m/s (a)for the virtual section with 3km (b) for the test section with 6km

Table 1. The prediction errors in the frequency of the strong wind

The interval of the sub-section	50m	100m	200m	400m	1000m	2000m
Complete correlation	-49.1%	-49.1%	-49.1%	-49.1%	-49.1%	-49.1%
No correlation	1088.5%	522.5%	217.5%	94.2%	-18.2%	-32.9%
Proposed method	-1.5%	-1.7%	-2.0%	-6.6%	-32.9%	-32.9%

4 TRAIN REGULATION COSIDERING THE WIND DIERCTION AND WIND FENCE

As the critical wind speed of the train overturning changes considerably depending on wind directions and a wind fence, an efficient train regulation is expected by considering these factors. Imai et al. (2002) proposed a train regulation considering the wind directional effect and showed a good result. In this section, the effects of the train regulation considering the wind direction and the wind fence are examined based on the critical wind speed of the train overturning.

4.1 *The outline of the regulation of the train operation*

To take the wind directional effect of the critical wind speed into account, wind direction factor $C_c(\phi,V)$ is defined as follows:

$$C_c(\phi,V) = \frac{W_C(\phi_{DNGER},V)}{W_C(\phi,V)} \tag{11}$$

where $W_c(\phi,V)$ is the critical wind speed of the train overturning, which is a function of the relative angle ϕ between the railway direction and the wind direction as well as the train speed V. ϕ_{DANGER} is the angle at which the critical wind speed of the overturning has the smallest value, i.e. the most dangerous direction. The critical wind speed of the train overturning used in this study was calculated by the method proposed by Hibino and Ishida (2003) as shown in Figure 6. The critical wind speeds are low at the relative angle between about 40 and 110 degree and go up remarkably as the angle decreases or increases regardless of the train speed.

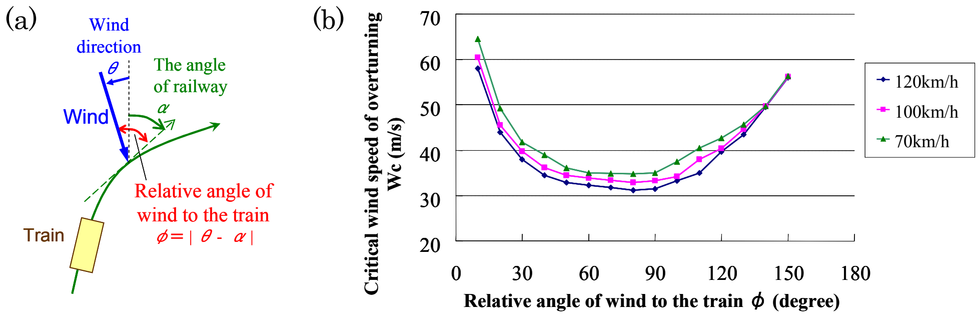


Figure 6. (a) Definition of the wind direction and (b) the critical wind speed of the train overturning with the wind direction

To take the effect of the wind fence into account, a wind fence factor $C_f(\phi)$ is also defined as follows:

$$C_f(\phi) = \sqrt{(C_n \sin\phi)^2 + (C_r \cos\phi)^2} \tag{12}$$

where $C_n = 0.83$ and $C_r = 1.0$ are the wind reduction factors for the wind component perpendicular and parallel to the wind fence respectively.

The frequency of the regulation of the train operation can be calculated by substitution of the derived wind speed to Equation (9) as follows:

$$P_{nk} = P\left[\max\left\{\hat{u}_{\text{site}}(t) \times C_*(\phi,V)\right\} > u^{\text{limit}}\right] \tag{13}$$

where $C_*(\phi,V)$ is a factor representing either the wind direction factor $C_c(\phi,V)$ or the product of the wind direction factor and the wind fence factor, and is multiplied to the maximum gust $\hat{u}_{\text{site}}(t)$ derived by proposed method in Section 2 to consider effects of the wind direction and the wind fence. In this study, the train speed V is assumed to be 120km/h.

4.2 *Effects of the wind direction and the wind fence on the train regulation*

The frequencies of the train regulation considering the wind direction and the wind fence in the 6km test section are shown in Figure 7. The frequency decreases from 0.16% to 0.11%, when the wind direction is considered and the frequency further decreases to 0.08% when the wind fences are installed in the test section. It is obvious that the frequency of the train regulation will be decreased with the equivalent safety by considering the effect of wind direction and the wind fence.

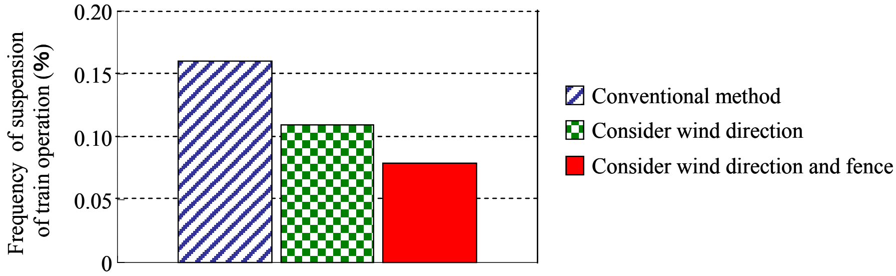


Figure 7. The frequency of the strong gust over regulation wind speed, 25m/s

5 CONCLUSION

In this study, prediction methods for the strong wind and its frequency along railway are proposed and applied to a train regulation, considering wind direction and wind fence. Following results are obtained.

1) A prediction method for the strong gust was proposed, which can take the effect of not only local terrain but also meteorological conditions into account and predicted maximum gust by this method shows good agreement with the measurement.
2) A time series based method for the prediction of the frequency of strong wind in a control section was proposed. The predicted frequency by the proposed method shows good agreement with the measurement, while the conventional methods underestimates or overestimates the frequency.
3) The frequency of the regulation of the train operation at the 6km test section decreases from 0.16% to 0.11% when the wind direction is considered and further decreases to 0.08% when the wind fence is installed.

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