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Prediction of frequency distribution of strong crosswind in a control section for train operations by using onsite measurement and numerical simulation

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ABSTRACT

In this study, a prediction method for strong wind using onsite measurement and numerical simulation is used to take account of the effects of complex terrain. The predicted maximum winds agree well with the measurements. A time series based method is proposed to predict the frequency of exceedance of strong crosswind in a control section. The predicted frequency of exceedance of strong crosswind agrees well with the measurements, while conventional methods based on only statistical data underestimate or overestimate the frequency. The proposed method is applied in order to estimate the regulation frequency in train operation, considering train speed, wind direction, and windbreaks. The regulation frequency at a target control section of 6 km decreases from 0.16% to 0.14% when the train speed is reduced. The frequency decreases from 0.16% to 0.11% if the wind direction is considered. The construction of the windbreaks decreases the frequency further to 0.08%.

1. Introduction

In railways, some accidents that lead to train turning over or derailment are caused by strong crosswinds, and the regulation of railway operation became stricter after these accidents were reported (Fujii et al., 1995). After obtaining the knowledge that the maximum instantaneous wind speed is highly dominant to the overturning of the train from a study of the accident in 1986 (Nakao), the regulation in Japan has subsequently been governed by the measured maximum instantaneous wind speed in a control section set within a continuous railway track. As Kunieda (1972) and Hibino et al. (2011). mentioned, critical wind speed of train overturning can be improved if the train speed is reduced. Therefore, the train speed is reduced or the train is stopped if measured or predicted wind speed in the control section exceeds a threshold set by a railway company considering the critical wind speed of train overturning. By this regulation, train delay time increases if the measured or predicted wind speed exceeds the threshold frequently. In order to reduce the duration of the regulation, Fujii (1998), Matsuda et al. (1997), and Imai et al. (2002). proposed regulation methods considering wind directions. Tanemoto et al. (2005), Avila-Sanches et al. (2014). studied the effect of windbreaks to reduce the side wind force induced on the train, and East Japan Railway Company introduced the windbreaks along the railway tracks (East Japan Railway Company, 2016). In order to realize efficient operation control under the strong wind, the effectiveness of countermeasures should be validated quantitatively by prediction for the frequency of exceedance of strong crosswind in the control section.

There are two methods to predict the frequency of exceedance of strong crosswind in the control section. In one method (Hibino et al., 2011), the frequency is predicted from wind speed measured by one anemometer installed in the control section, which is used by many railway companies especially in Japan. The frequency by this method can be estimated by only considering the measured wind speed. However, the frequency might be underestimated if the strongest wind does not brow at the measurement site. In another method proposed by Matschke et al. (2000). and Cleon et al. (Cléon et al., 2002), the control section is divided into number of sub-sections and the strong wind in each sub-section is predicted by a combination of measured wind speed and those obtained from numerical simulation. Although this method can take account of the winds which blows at sites where the anemometer is not installed, the frequency of strong crosswind might be overestimated because it is assumed that there is no correlation between the wind speeds in sub-sections.

In this study, a prediction method for maximum wind speed and direction at sites along a railway track is proposed by using onsite measurement and numerical simulation. The predicted maximum wind speed and direction by the proposed method are verified by measured those at the sites. Then, a new method is proposed to predict the frequency of exceedance of strong crosswinds in a control section with consideration

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of the correlation between strong crosswinds at different sub-sections. The accuracy of the proposed method is evaluated and the disadvantage of the existing methods is clarified by comparison with the onsite measurement. Finally, the effect of countermeasures against the strong crosswind, such as reducing train speed, regulation considering wind directions, and installation of windbreaks, are assessed using the proposed method.

2. Strong wind prediction along a railway track

In this section, maximum wind speed and wind direction are predicted by a method using an onsite measurement and numerical simulation technique. In this method, the effects of local terrain on the wind speed and the wind direction are taken into account.

2.1. Prediction of maximum wind speed and wind direction

The wind speed ratio, S_{pr}, and change in wind direction, D_{pr}, between a reference site, where an anemometer is installed, and a prediction site, where wind speed and direction are to be estimated, are obtained from the numerical simulation. A time series of mean wind speed and wind direction at the prediction site, u_{p} and θ_{p}, are estimated by multiplying the wind speed ratio and adding the change in wind direction to a time series of measured mean wind speed, u_{r}, and wind direction, θ_{r}, at the reference site as:

$$u_{\mathrm{p}} = u_{\mathrm{r}} \times S_{\mathrm{pr}} \tag{1}$$

$$\theta_{\mathrm{p}} = \theta_{\mathrm{r}} + D_{\mathrm{pr}} \tag{2}$$

where subscripts p, r, and pr means the prediction site, the reference site, and the relationship between the prediction site and the reference site respectively. The maximum wind speed $\widehat{u}_{\mathrm{p}}$ at the prediction site can be calculated by multiplying the gust factor G_{p}, defined by the ratio of the maximum to the mean speed, to the predicted mean wind speed u_{p} as:

$$\widehat{u}_{\mathrm{p}} = u_{\mathrm{p}} \times G_{\mathrm{p}} = u_{\mathrm{r}} \times S_{\mathrm{pr}} \times G_{\mathrm{p}} \tag{3}$$

Because wind directions of the maximum winds, $\widehat{\theta}_{\mathrm{P}}$, are consistent with the wind directions of the mean winds (Misu and Ishihara, 2012), it can be approximated by

$$\widehat{\theta}_{\mathrm{p}} \cong \theta_{\mathrm{p}} \tag{4}$$

The gust factor G_{p} can be estimated using the peak factor k_{p}, which is defined by the ratio of the maximum to the standard deviation of fluctuating wind speed and proposed by Ishizaki (1983), and the turbulence intensity I_{p}, which is obtained by a microscale wind prediction model (Yamaguchi et al., 2003; Ishihara and Hibi, 2002), as follows:

$$G_{\mathrm{p}} = 1 + k_{\mathrm{p}} I_{\mathrm{p}} \tag{5}$$

$$k_{\mathrm{p}} = \frac{1}{2} \ln \frac{T}{t} \tag{6}$$

where T is a reference time and t is an averaging time. In this study, the reference time is 60 s and the averaging time is three seconds.

The flow chart of the proposed method is shown in Fig. 1.

2.2. Prediction of wind speed and wind direction by numerical simulation

The microscale wind climates in a target domain can be predicted using a numerical simulation (Yamaguchi et al., 2003; Ishihara and Hibi, 2002; Liu et al., 2016a, 2016b). The governing equations of this model in this study, equations of continuity and momentum conservation, are as follows:

$$\frac{\partial \rho \overline{u}_j}{\partial x_j} = 0 \tag{7}$$

$$\frac{\partial \rho \overline{u}_i}{\partial t} + \frac{\partial \rho \overline{u}_j \overline{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) \tag{8}$$

where $\overline{u}_i$ and u'_i are average wind speed and fluctuating wind speed in x_i direction. ρ is density, $\overline{p}$ is average pressure, and μ is viscosity of fluid.

Reynolds stress $-\rho\overline{u_i' u_j'}$ can be approximated by a linear eddy viscosity model as:

$$\rho \overline{u_i' u_j'} = \frac{2}{3}\rho k \delta_{ij} - \mu_{\mathrm{t}}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{9}$$

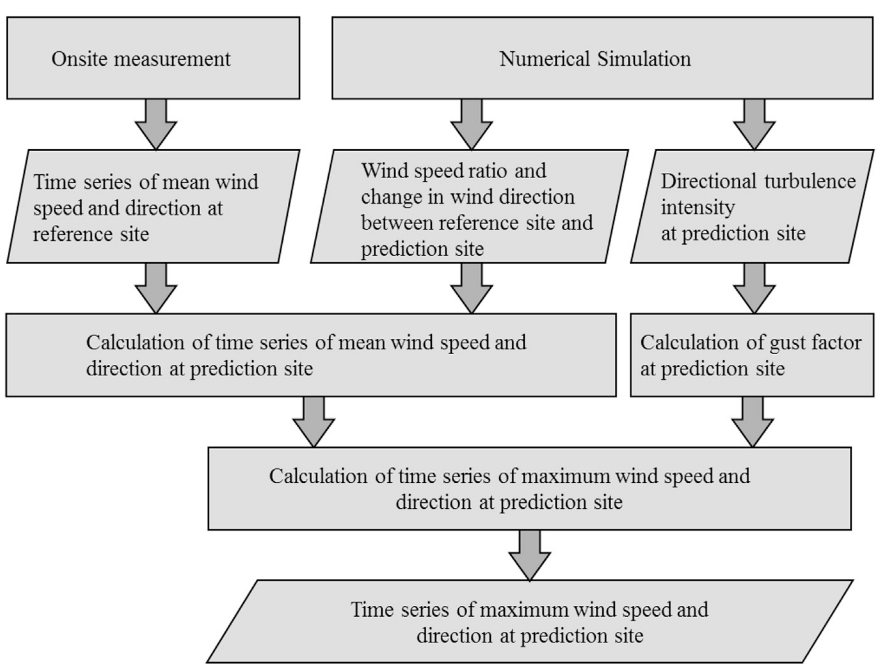

Fig. 1. Flow chart of prediction method for strong wind using onsite measurement and numerical simulation.