Evaluation of the Aerodynamic Force on a Railway Vehicle in Half-bank Half-cut Line Sections

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The running safety of railway vehicles exposed to strong cross winds is evaluated by means of an aerodynamic coefficient obtained from wind tunnel tests. There are many types of section topography along actual railway lines, but the aerodynamic coefficient is sought for seven standard types of structure. Many lines close to the coast or rivers are often flanked by a slope on one side and a bank on the other (half-bank half-cut sections), and sections like this are treated as embankments. However, in sections with a high cut on the downwind side, the lateral aerodynamic force acting on the train is different from that in sections of normal embankments. Therefore, wind tunnel tests were conducted to obtain the aerodynamic coefficient for half-bank half-cut sections.

Keywords: railway vehicle, cross wind, wind tunnel test, half-bank and half-cut, embankment

1. Introduction

The derivation of aerodynamic coefficients used in the equation (hereafter, it shall be referred to as the RTRI’s detailed equation) provided by Railway Technical Research Institute (RTRI) to calculate critical overturning wind speed in existing studies is based on seven standard types of railway structures [1]. These seven structures comprise a single-track embankment, double-track viaducts (girder heights: 1.0, 3.5, and 6.0 m), and single-track bridges (girder heights: 1.0, 2.0, and 3.5 m). Many types of section topographies exist along actual railway lines. However, the aerodynamic coefficients for some of them may differ from those based on these seven standard types of structures. One such example relates to section topographies located near the coast, which are often flanked by an embankment on the ocean side and a high slope (cutting) on the inland side (half-bank half-cut sections).

Currently, the aerodynamic coefficients for the single-track embankment are applied to such sections to calculate the critical overturning wind speed using RTRI’s detailed equation [2]. However, the aerodynamic coefficients for half-bank half-cut sections are different from those of single-track embankments due to the effect of the high cutting on the downwind side of the train.

The present study conducted wind tunnel tests on a train on a half-bank half-cut line section to investigate various parameters, including wind angle, train set (leading and middle vehicles), train position, and cutting shape. The goal of this study was to understand the aerodynamic forces acting on the train, and compare the results with those of a train on a single-track embankment.

2. Wind tunnel tests

2.1 Wind tunnel facility

The wind tunnel tests were conducted on a closed test section of the RTRI’s large-scale low-noise wind tunnel. The closed test section was 5 m in width, 3 m in height, and 20 m in length, and a turntable was provided on the floor (in the center) 16.8 m downstream of the upstream edge of the test section. Models were placed on this turntable to measure the aerodynamic forces. Further, barriers, spires, and roughness blocks were provided upstream of the turntable to generate a turbulent boundary layer (exponent: 0.26) to simulate natural wind. A right-handed Cartesian coordinate system was used to indicate the main flow direction as X, the cross direction as Y, and the vertical upward direction as Z, with the origin being the center of the floor, widthwise, at the upstream edge of the closed type test section. Figure 1 shows the closed type test section.

![Fig. 1 Positions of turbulent boundary layer generators inside the closed type test section (exponent: 0.26)](image-url)
Fig. 2 Test conducted in the wind tunnel (view from upstream)

Figure 2 shows the test being conducted in the wind tunnel. A Pitot tube, which controls the wind speed in the tunnel, was placed at X = 11.800 m, Y = 1.504 m, and Z = 1.800 m, and the wind speed indicated by the Pitot tube was referred to as test wind speed $U_c$. The test wind speed was 30 m/s.

### 2.2 Aerodynamic force evaluation methods

The aerodynamic forces required for the evaluation of critical overturning wind speed consist of side force $S$, lift $L$, and rolling moment $M$ (hereinafter the “moment”), and their positive directions are shown in Fig. 3. The coordinate axes of the aerodynamic forces are fixed to the vehicle (body axes), which simultaneously change as the wind angle $\beta$ changes.

**Fig. 3 Aerodynamic forces acting on model train**

The specifications of the model vehicles used to calculate the aerodynamic coefficients are shown in Table 1. The side force coefficient and lift coefficient are the mean aerodynamic forces (side force and lift) divided by the mean dynamic pressure and body side area $A$ (expressed as body height $h$ × body length $l$, and not the projected area). The moment coefficient was obtained by dividing the moment by mean dynamic pressure, body side area $A$ and body height $h$. The mean aerodynamic forces were obtained from the data recorded for 42 s at the sampling frequency of 100 Hz. The mean dynamic pressure was calculated using the time-mean value of the wind speed $U_{BL} (Z_r)$ at the reference point $Z_r$ for the calculation of the aerodynamic coefficient. The center of moment was at one-half of the body height (body center), and the moment coefficient was positive when the direction of overturning was from upwind to downwind. The aerodynamic coefficients can be calculated using (1) to (3).

**Side force coefficient:** $C_S = \frac{S}{\frac{1}{2} \rho (U_{BL} (Z_r))^2 A}$  \hspace{1cm} (1)

**Lift coefficient:** $C_L = \frac{L}{\frac{1}{2} \rho (U_{BL} (Z_r))^2 A}$  \hspace{1cm} (2)

**Moment coefficient:** $C_M = \frac{M}{\frac{1}{2} \rho (U_{BL} (Z_r))^2 Ah}$  \hspace{1cm} (3)

### 2.3 Models for wind tunnel tests

The cross-sectional shape of the half-bank half-cut line section used in the wind tunnel tests is shown in Fig. 4 along with the test parameters (the dimensions are full-scale, proportional to 8 m in the figure). The slope gradient and height of the embankment are fixed at 1:1.5 (33.7 degrees) and 8 m, respectively, and the slope of the cutting was fixed at 45 degrees. The parameters for the wind tunnel tests were as follows: cutting height $H_C$, distance between the cutting edge (toe of the slope) and the center of the track $A_C$, distance between the embankment edge (top of the slope) and the center of the track $A_E$, and distance between the embankment edge (top of the slope) and the cutting edge (toe of the slope) $A = A_C + A_E$. The subscript “C” stands for “Cutting” and “E” for “Embankment.”

The train model used in the wind tunnel tests simulated a commuter train, the roof of which had a radius of curvature of 5000 mm, with running boards attached, and hereafter, referred to as train R5000.

The wind tunnel test conditions are listed in Table 2. When the cutting height $H_C$ was large, the blockage ratio relative to the closed test section type was high, and therefore, a 1:40 scale model was used for the cutting height $H_C$ of 10 m or less, and a 1:60 scale model was used for the cutting heights of 10 m and 15 m (both the 1:40 and 1:60 scales were used for testing with the cutting height of 10 m). The choking rates at the cutting heights $H_C$ of 10 m and 15 m using...
the 1:40 and 1:60 scales were 15% and 13%, respectively. The wind profile remained unchanged regardless of the scale.

### Table 2 Wind tunnel test conditions

| Scale | Hc | Vehicles | β=60° | β=90° | β=120° | β=150° |
|-------|----|----------|--------|--------|---------|---------|
| 1m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 2m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 3m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 4m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 1:60  | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 6m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 7m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 8m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 9m    | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 10m   | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |
| 1:60  | Leading | - | - | - | - | - |
|       | Middle | - | - | - | - | - |

Legends (See section 3.6 for the meaning of color)

- : Leading vehicle, 90°
- : Leading vehicle, 70°
- : Leading vehicle, 50°
- : Leading vehicle, 30°
- : Middle vehicle, 90°
- : Middle vehicle, 70°
- : Middle vehicle, 50°
- : Middle vehicle, 30°

3. Results of wind tunnel tests

This section describes the calculation of the side force coefficient, which significantly influences the overturning of trains, based on the wind tunnel test results.

The side force coefficient ratio was defined as, 'the side force coefficient obtained under the respective wind tunnel half-bank half-cut section test conditions divided by the side force coefficient obtained for the single-track embankment under the identical vehicle (leading and middle vehicles), wind angle, and scale conditions,' and is hereinafter referred to as "the side force coefficient ratio."

#### 3.1 Aerodynamic coefficients for single-track embankment

Before explaining the results of the wind tunnel tests on the half-bank half-cut section, first, the aerodynamic coefficients for the single-track embankment are shown in Fig. 5. The wind angles were β = 90, 70, 50, and 30 degrees for the 1:40 model, and β = 90 and 70 degrees for the 1:60 model. The figure shows that the aerodynamic coefficients for the 1:40 and 1:60 models were approximately the same for the wind angles β = 90 and 70 degrees. Since the wind angles of 50 and 30 degrees were not tested on the 1:60 model in the wind tunnel for the single-track embankment, these aerodynamic coefficients were not obtained. To calculate the side force coefficient ratios for the 1:60 model at the wind angles β = 50 and 30 degrees, the side force coefficients for the 1:40 single-track embankment model at the wind angles β = 50 and 30 degrees were used, instead of those for the 1:60 single-track embankment model at the wind angles β = 50 and 30 degrees.

#### 3.2 Relationship between cutting height Hc and side force coefficient ratio

This section explains the effect on the side force coefficient ratio when Hc changed while A and Ae were fixed.

Figure 6 shows the relationship between cutting height Hc and the side force coefficient ratio for middle vehicles at the wind angle β = 90°. The side force coefficient ratio generally increased or did not change in the case of the leading vehicle when the cutting height Hc increased from 1 m to about 4 m when the wind angle was not 90 degrees. When the cutting height Hc increased to 15 m from about 4 m, the side force coefficient ratio showed a decreasing tendency.

#### 3.3 Relationship between distance between the top of the slope and the center of track Ais, and side force coefficient ratio

This section describes the effect of change in the distance...
between the top of the slope and the center of track $A_r$ on the side force coefficient ratio while the distance between the top and the toe of slope $A$ and the cutting height $H_C$ were fixed.

Figure 7 shows the relationship between the distance between the top of the slope and the center of the track $A_r$, and the side force coefficient ratio for middle vehicles for the wind angle $\beta = 90^\circ$. Although the figure does not indicate all the conditions, the side force coefficient ratio showed a decreasing tendency when the distance between the top of the slope and the center of track $A_r$ increased, regardless of the vehicle type and wind angles being measured.

![Fig. 7 Relationship between distance between top of slope and center of track $A_r$, and side force coefficient ratio](image)

### 3.4 Distance between top of slope and center of the track $A$ and side force coefficient ratio

This section explains the effect of change in the distance between the top and the toe of slope $A$ on the side force coefficient ratio while cutting height $H_C$ and the distance between the top of slope and the center of track $A_r$ were fixed. Table 3 summarizes the increasing/decreasing tendencies. Red indicates an increase in the side force coefficient ratio when the distance between the top and the toe of slope $A$ was increased, whereas yellow indicates almost no change when $A$ was increased, blue indicates a decrease when $A$ was increased, and orange indicates an increase when $A$ was increased up to 10 m, but almost no change was observed thereafter. Table 3 reveals that the color blue (decrease relative to the distance between the top and the toe of slope $A$) is predominant in the upper region for middle vehicles and the upper left region for the leading vehicle, and red (increase relative to $A$) is predominant in the lower region for the middle car and the lower right region for the leading vehicle. Figure 8 shows the relationship between the distance between the top and the toe of slope $A$ at a wind angle $\beta = 90^\circ$ for middle vehicles and the side force coefficient ratio.

![Fig. 8 Relationship between distance between top and toe of slope $A$, and side force coefficient ratio](image)

### Table 3 Increasing/decreasing tendencies of side force coefficient ratio when distance between top and toe of slope $A$ was increased

| $H_C$ | $A_r$ | $A$ | Wind angle | $H_C$ | $A_r$ | $A$ | Wind angle |
|-------|-------|-----|------------|-------|-------|-----|------------|
| 1 m   | 2 m   | 6 m | 90°        | 5 m   | 15 m  | 2.84 m | 90°        |
| 2 m   | 6 m   | 10 m| 70°        | 5 m   | 15 m  | 2.84 m | 70°        |

Legend (Red: Increase, Yellow: No change, Blue: Decrease, Orange: No change after increasing up to $A = 10$ m)

### 3.5 Maximum side force coefficient ratio

This section describes the maximum side force coefficient ratio for the vehicle and wind angle $\beta$ being measured. The combination of the cutting height $H_C$, the distance between the top and the toe of slope $A$, and the distance between the top of the slope and the center of the track $A_r$ (the measured vehicle and wind angle $\beta$ were fixed), under which the side force coefficient ratio was at its maximum, were identified from the wind tunnel test conditions. The results showed that the side force coefficient ratio was the highest under the conditions indicated in red in Table 2. However, the difference in the side force coefficient ratios under $(H_C, A, A_r) = (3\, m, 6\, m, 2.84\, m)$ and $(H_C, A, A_r) = (4\, m, 6\, m, 2.84\, m)$ at the wind angle of 90 degrees for middle vehicles and the wind angle at 70 degrees for the leading vehicle was 0.03. This revealed the tendency for maximization of the side force coefficient ratio when $H_C$ was about 3 m and $A_r$ was 2.84 m. Further, the distance between the top and the toe of slope $A$ when the side force coefficient ratio peaked, varied according to the measured vehicles and wind angles, and thus, the side force coefficient ratio was at its maximum when $A$ was 6 m at all wind angles for the middle vehicles and wind angles of 90 and 70 degrees for the leading vehicle, and 20 m at wind angles of 50 and 30 degrees for the leading vehicle.

Figure 9 shows the relationship between the wind angle $\beta$ and side force coefficient ratio. Figure 9 shows that the maximum side force coefficient ratio was greater than 1 for all measured vehicles at all wind angles. This indicates that conditions existed where the side force coefficient was greater than that for a single-track embankment for all measured vehicles under all wind angles.

In the paragraph above, the maximum side force coefficient ratio was obtained when cutting heights $H_C$ were from 1 m to 15. Here, $H_C$ was limited to the 10 to 15 m range, and the maximum side force coefficient ratio for this range was obtained. The results showed that the side force coefficient ratio was the highest under the conditions indicated in blue in Table 2.
Figure 10 shows the relationship between the wind angle \( \beta \) and the maximum side force coefficient ratio (cutting height \( H_c \) was limited to 10 and 15 m).

Limiting \( H_c \) to 10 and 15 m revealed that the maximum side force coefficient ratio was smaller than 1 for all measured vehicles under all wind angles. In other words, the side force coefficient for the half-bank half-cut line section was lower than that for the single-track embankment when the cutting height \( H_c \) was limited to 10 and 15 m.

### 4. Application of aerodynamic coefficients for the half-bank half-cut line section

Since there were numerous parameters for the half-bank half-cut line section, it was difficult to identify which aerodynamic coefficients should be applied to the actual topography. To resolve this issue, this section proposes a method to apply the aerodynamic coefficients for the single-track embankment, rather than the half-bank half-cut line section, using constant multiplication.

For simplicity, the coefficient with the greatest effect on the critical overturning wind speed, that is, the side force coefficient, was selected for constant multiplication from three types of aerodynamic coefficients.

An evaluation index was calculated from the viewpoint of vehicle overturning, wherein the moment coefficient around the downwind rail (contact point of the wheels and rail on the downwind side) \( C_{M,lee} \) was estimated as follows:

\[
C_{M,lee} = \frac{C_{S}h_{V}}{h} + \frac{C_{L}l_{S}}{2h} + C_{M} \quad (4)
\]

where \( h \), \( h_{V} \), and \( l_{S} \) in (4) are defined in Table 1.

The method for determining the constant \( k \) required for multiplication with the side force coefficient for a single-track embankment \( C_{S} \) is explained here. Firstly, the side force coefficient for single-track embankment \( C_{S,emb} \), lift coefficient \( C_{L,emb} \), moment coefficient \( C_{M,emb} \), and constant \( k \) are substituted in the equation below:

\[
C_{M,lee}(k) = \left( \frac{kC_{S,emb}h_{V}}{h} + C_{L,emb}l_{S} + C_{M,emb} \right) \quad (5)
\]

Thus, the moment coefficient around the downwind rail \( C_{M,lee}(k) \) is calculated, where the side force coefficient alone is multiplied by \( k \) relative to the aerodynamic coefficients for a single-track embankment. The subscript \( emb \) stands for “Embarkment,” \( C_{0} \), \( C_{L} \), and \( C_{M} \) on the right-hand side of Equation (4) are substituted with \( kC_{S,emb}, C_{L,emb}, \) and \( C_{M,emb} \), respectively.

Next, \( C_{M,lee}(k) \), which is calculated in Equation (4) using the aerodynamic coefficients according to the parameters of the half-bank half-cut line section, is compared with \( C_{M,lee}(\beta) \), which is calculated in Equation (5) using the aerodynamic coefficients for the single-track embankment. If \( C_{M,lee}(k) \) is smaller than \( C_{M,lee}(\beta) \) for the half-bank half-cut line section, the constant multiplier \( k \) is small, and therefore, it will not be applicable from the viewpoint of safety/vehicle overturning. On the other hand, if \( C_{M,lee}(k) \) is greater than \( C_{M,lee}(\beta) \) for the half-bank half-cut line section, \( kC_{S,emb} \) can be used as the side force coefficient; \( C_{L,emb} \), as the lift coefficient; and \( C_{M,emb} \), as the moment coefficient for the aerodynamic coefficients of the half-bank half-cut line section, from the viewpoint of vehicle overturning. This comparison process is continued, increasing the constant \( k \) until an appropriate or “safe” value for \( k \) is identified.

An example of calculating the constant is described below. Figure 11 shows the moment coefficient around the downwind rails when the cutting height \( H_c \) changed under the following conditions: wind angle \( \beta = 90^\circ \), \( A = 6 \) m, and \( A_{0} = 2.84 \) m. The moment coefficient ratio around the downwind rail was obtained by dividing the moment coefficient around the downwind rail for the half-bank half-cut section \( C_{M,lee} \) by the that for the single-track embankment for identical vehicle, wind angle, and scale conditions (i.e., \( C_{M,lee}(1.0) \)).

Figure 11 also shows the derivation of the moment coefficient ratio around the downwind rails by dividing \( C_{M,lee}(1.0), C_{M,lee}(1.2), \) and \( C_{M,lee}(1.4) \), each of which were calculated using the aerodynamic coefficients for a single-track embankment for a middle car at the wind angle \( \beta = 90^\circ \), by \( C_{M,lee}(1.0) \).

Firstly, when constant \( k \) was set to 1.0, \( C_{M,lee}(1.0) \) at \( H_c = 10 \) and 15 m exceeded \( C_{M,lee}(1.0) \). Thus, it was determined that the aerodynamic coefficients for the single-track embankment for middle vehicles at the wind angle \( \beta = 90^\circ \) could be applied when the cutting height \( H_c \) was 10 m or more. On the other hand, the constant \( k \) should be reconsidered when the cutting height \( H_c \) is less than 10 m, because \( C_{M,lee}(1.0) \) is greater and the aerodynamic coefficients for the single-track embankment for middle vehicles at the wind angle \( \beta = 90^\circ \) cannot be applied.

Next, when the constant \( k \) was set to 1.2, \( C_{M,lee}(1.2) \) exceeded \( C_{M,lee}(1.0) \) at \( H_c = 1, 7, 8, 10, \) and 15 m. Therefore, it was determined that the aerodynamic coefficients for the single-track embankment for middle vehicles at the wind angle \( \beta = 90^\circ \), in which only the side force coefficient is multiplied by 1.2, could be applied as the aerodynamic coefficients for these conditions at these values of \( H_c \).

Finally, when the constant \( k \) was set to 1.4, \( C_{M,lee}(1.4) \) exceeded \( C_{M,lee}(1.0) \) at all cutting heights \( H_c \). Therefore, it was
determined that the aerodynamic coefficients for the single-track embankment for middle vehicles at the wind angle $\beta = 90^\circ$, in which only the side force coefficient is multiplied by 1.4, could be applied as the aerodynamic coefficients for these conditions at these cutting heights $H_C$.

Setting the constant $k$ to 1.4 for all cutting heights $H_C$ is a safe side evaluation, but some conditions already take safety into consideration, and therefore, it is desirable to categorize these conditions using parameters and respectively determine the appropriate constant $k$.

![Diagram showing calculation of constant $k$]

Fig. 11 Example showing calculation of constant $k$

### 5. Conclusion

This paper investigated the aerodynamic coefficients for the leading and middle vehicles of the R5000 train on a half-bank half-cut line section by conducting wind tunnel tests using the following parameters: cutting height $H_C$, distance between the embankment edge and the center of track $A_E$, and distance between the embankment edge and the cutting edge $A$. The test results were organized by according to the side force coefficient ratio, which was obtained by dividing the side force coefficient for each wind angle from the wind tunnel tests by the aerodynamic coefficients obtained for the R5000 train on the single-track embankment for identical vehicle, wind angle and scale conditions. The results were as follows.

1. The side force coefficient ratio generally increased or showed no change when the cutting height $H_C$ increased from 1 m to about 4 m regardless of the measured vehicles or the wind angles. When $H_C$ increased to 15 m from about 4 m, the side force coefficient ratio showed a decreasing tendency.

2. The side force coefficient ratio showed a decreasing tendency when $A_E$ increased regardless of the measured vehicles and wind angles.

3. The increasing/decreasing tendencies of side force coefficient ratio when $A$ increased varied according to the measured vehicles and wind angles.

4. For some $(H_C, A, A_E)$ conditions, the side force coefficient exceeded that for the single-track embankment for all vehicles under all measured wind angles.

5. A constant multiplication method was presented to enable application of the side force coefficients for the single-track embankment instead of applying the aerodynamic coefficient for the half-bank half-cut line section.

### Acknowledgement

The authors would like to thank Mr. K. Tanemoto and Mr. T. Kato of Tess Co., Ltd.

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