ON THE REVISION
OF WIND-RESISTANT DESIGN MANUAL FOR HIGHWAY BRIDGES

by

Hiroshi Sato[1)] and Nobuyuki Hirahara[2)]

ABSTRACT

The existing Wind Resistant Design Manual for Highway Bridges was outlined first. Then some descriptions of the Manual to be improved or revised were introduced.

Detailed description is required for wind resistant design of towers and cables. The description for bridge girders should be improved or revised so that the Manual may be applicable to plate girder bridges, bridges with noise barriers, and bridges located closely to each other. Recent field observation results on turbulence intensity of wind and structural damping should be incorporated.

KEYWORD: Wind-Resistant Design, Highway Bridges, Manual, Revision

1. INTRODUCTION

In Japan, the wind-resistant design of highway bridges up to the span length of 200m are conducted according to the Wind Resistant Design Manual for Highway Bridges [1], [2] (hereinafter referred to as 'the Manual'), which was published in 1991. This Manual is also applicable to the highway bridges up to the span length of 300m with minor modification of its provisions.

The contents of 'the Manual' are as follows.

(1) GENERAL REMARKS
(2) GUIDELINE OF WIND RESISTANT DESIGN
(3) DESIGN WIND LOAD
(4) WIND PROPERTIES USED IN DESIGN
(Basic Wind Speed, Design Wind Speed, Intensity of Turbulence, etc.)
(5) WIND-INDUCED VIBRATIONS OF BRIDGE GIRDERS
(Prediction, Evaluation, Method of Alleviation, Flutter, Galloping, Vortex-Induced Vibrations, Gust Responses)
(6) WIND-INDUCED VIBRATIONS OF TOWERS AND BRIDGE MEMBERS
(7) WIND RESISTANT DESIGN AT ERECTION STAGES
(8) WIND TUNNEL TESTING METHODS

Although the formulae to predict wind-induced vibrations of bridge girders are provided in 'the Manual', only the outlines are described for towers and cables. Detailed description of the design methods for towers and cables has been required.

In 'the Manual', assumed bridge types were suspension bridges, cable-stayed bridges and box girder bridges. Recently, plate girder bridges, whose torsional rigidity is smaller than that of box girder bridges, have been applied to longer span length. Noise barriers, which make girders bluff, are often attached to highway bridges in city area. In some cases, two bridges are constructed very closely to each other, which may cause buffeting problems. Wind resistant design methods for these bridges have also been required.

From these reasons, revision work of 'the Manual' was started at the committee for wind resistant design manual of the Japan Road Association in 2000. In this paper, wind resistant design methods described in 'the Manual' are outlined first. Then some descriptions of 'the Manual' to be improved or revised are introduced.

2. OUTLINE OF THE WIND RESISTANT DESIGN METHODS FOR HIGHWAY BRIDGES DESCRIBED IN THE MANUAL

The main features of 'the Manual' are as follows.

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1) Director, Structures Research Group, Public Works Research Institute, Independent Administrative Institution, Minamihara 1-6, Tsukuba-shi, Ibaraki-ken, 305-8516, Japan
2) Team Leader for Bridge Structure, ditto

a. The basic wind speeds of the whole country are provided.
b. The design wind speed and the properties of wind turbulence can be obtained considering the altitude of structure and the terrain around the structure.
c. The critical wind speed for flutter and galloping can be predicted by simple formulae as well as by wind tunnel testing.

The formula for prediction of critical wind speed of flutter is as follows:

$$U_{cf} = 2.5\ f_{\theta} B \quad (1)$$

where, U_{cf}: critical wind speed for flutter, f_{θ}: natural frequency of the 1st torsional mode, B: width of bridge section.

The formula for prediction of critical wind speed of galloping is as follows:

$$U_{cg} = 8\ f_h B \text{ ; when angle of attack is almost 0 deg.} \quad (2)$$

$$U_{cg} = 4\ f_h B \text{ ; when angle of attack is positive.} \quad (3)$$

where, U_{cg}: critical wind speed for galloping, f_h: natural frequency of the 1st bending mode.

d. The critical wind speed and amplitude of vortex-induced vibrations can be predicted by simple formulae as well as by wind tunnel testing. The effects of turbulence on vortex-induced vibrations are incorporated.

The formulae for prediction of critical wind speed and amplitude of vortex-induced vibrations are as follows:

$$U_{cv} = 2.0\ f_h B \text{ --- bending} \quad (4)$$

$$U_{cv} = 1.33\ f_{\theta} B \text{ --- torsion} \quad (5)$$

$$A_c = A_e E_{ms} E_t \quad (6)$$

$$A_e = \beta_{ds} \cdot 0.05 \cdot (d/B)/(m_r\ \delta_h) \text{ --- bending (in h/B)} \quad (7)$$

$$A_e = \beta_{ds} \cdot 13.2 \cdot (d/B)^3/(Ip_r\ \delta_{\theta}) \text{ --- torsion (in deg.)} \quad (8)$$

$$E_t = 1\text{-}15\ \beta_t (B/d)^{1/2} Iu^2 \geqq 0 \text{ --- bending} \quad (9)$$

$$E_t = 1\text{-}20\ \beta_t (B/d)^{1/2} Iu^2 \geqq 0 \text{ --- torsion} \quad (10)$$

where, U_{cv}: wind speed for the maximum amplitude of vortex-induced vibration, A_c: corrected maximum amplitude of vortex-induced vibration, A_e: maximum amplitude of vortex-induced vibration for rigid model in smooth flow, E_{ms}: correction factor for vibrational mode (about $4/\pi$), E_t: correction factor for the effect of turbulence, β_{ds}: correction factor for sectional shape, d: depth of bridge section, m_r, Ip_r: reduced mass or reduced mass moment of inertia, δ_h, δ_{θ}: structural damping (logarithmic decrement), β_t: correction factor for sectional shape, Iu: intensity of turbulence.

e. The method of verification of flutter, galloping and vortex-induced vibrations are provided.

For flutter and galloping, the following inequalities shall be satisfied,

$$U_{cf} > U_r \text{ --- Flutter} \quad (11)$$

$$U_{cg} > U_r \text{ --- Galloping} \quad (12)$$

$$U_r = U_d E_{r1} E_{r2} \quad (13)$$

$$U_d = U_{10} E_1 \quad (14)$$

where, U_{cf}: critical wind speed for flutter, U_{cg}: critical wind speed for galloping, U_r: reference wind speed for flutter and galloping, U_d: design wind speed, E_{r1}: correction factor for the effect of gust, E_{r2}: safety factor(1.2), U_{10}: basic wind speed, E_1: correction factor for altitude and terrains.

For vortex-induced vibrations, unless the following inequality (15) is satisfied, the maximum amplitude of the vortex-induced vibration shall be less than the allowable amplitude shown in equations (16) and (17).

$$U_{cv} > U_d \quad (15)$$

$$h_a = 0.04/f_h \text{ --- bending (in m)} \quad (16)$$

$$\theta_a = 2.28/(b\ f_{\theta}) \text{ --- torsion (in deg.)} \quad (17)$$

where, U_{cv}: wind speed for the maximum amplitude of vortex-induced vibration, h_a: allowable amplitude for bending vortex-induced vibration, θ_a: allowable amplitude for torsional vortex-induced vibration, b: distance between the deck center and the center of outmost lane.

f. The guideline of wind resistant design for bridge members and for bridges at their erection stages are described.
g. The standard wind tunnel testing methods are described.

The procedure of wind resistant design using the Manual is as follows. The wind properties (basic wind speed, design wind speed, turbulence intensity etc.) are decided first. The design wind load is calculated, and the static design of the bridge is made.

At this stage, where major dimensions of the bridge are determined, wind-induced vibrations to be studied further are chosen considering the design wind speed, the width of bridge section and the span length of the bridge. For a bridge with short span length, no study on wind-induced vibration is required.

For long-span bridges, wind-induced vibrations specified above should be predicted using the formulae provided in the Manual. Then the wind-induced vibrations are evaluated. The formulae were established considering past wind tunnel test results. Since the formulae are expressed by means of only a few parameters, the prediction error of the formulae is not negligibly small. Therefore, the formulae were established, so that their prediction may become safer. It means that evaluation 'good' based on the formulae is almost always 'good', however, evaluation 'no good' based on the formulae is not always 'no good' because of the safety margin of the formulae. In case that the evaluation based on the formulae turns out to be 'no good', the bridge engineer can modify the design or he can predict wind-induced vibrations more accurately by means of wind tunnel testing. The evaluation based on wind tunnel testing has priority over that based on the formulae.

3. DESCRIPTIONS IN THE MANUAL TO BE IMPROVED OR REVISED

3.1 Wind-induced Vibration of Towers

Towers of suspension and cable-stayed bridges are likable to vibrate due to wind especially during their free standing stages. Therefore field observation results and wind tunnel testing results on wind-induced vibrations of towers are described in ‘the Manual’. Countermeasures to the wind-induced vibrations, such as Tuned Mass Dampers, are also introduced in ‘the Manual’.

Prediction of their vibrations should be conducted through wind tunnel studies except for vortex-induced vibrations of twin parallel column type towers, for which the following prediction formulae were developed from wind tunnel study results, and are provided in ‘the Manual’.

$$U_{cv} = 10\, f_1\, D_T \qquad (18)$$

$$h_{max}/D_T = 4 \rho D_T^2 / (m_{eq}\ \delta_s) \qquad (19)$$

where, U_{cv}: wind speed for the maximum amplitude of vortex-induced vibration, f_1: first bending (along bridge axis) natural frequency of free-standing tower, D_T: length of the tower section along the bridge axis at the top, h_{max}: maximum amplitude of vortex-induced vibration in bending (along bridge axis) mode at the top of the tower, ρ: air density, m_{eq}: equivalent mass of tower, δ_s: structural damping of the tower (logarithmic decrement).

Similar formula for A-type towers, reverse Y-type towers and single column type towers have been required. Therefore the formulas are being developed based on existing wind tunnel study results.

3.2 Wind-induced Vibration of Cables

Cables of cable-stayed bridges have very small damping, and their vibrations are often observed. Cables in rain and wind are likable to vibrate because of rivulet. This vibration is called rain vibration. When cables are installed very close to each other, wake from an upstream cable may cause severe vibration to the downstream cable. This vibration is called wake galloping or wake induced flutter. Therefore field observation results and wind tunnel testing results on wind-induced vibrations of cables are described in ‘the Manual’. Countermeasures to the wind-induced vibrations, such as damping devices, are also introduced in ‘the Manual’.

In wind resistant design of cables, the following information would be useful:

(1) To what cables (length, diameter, mass, separation of cables, and so on) are countermeasures required?
(2) How much damping should we provide to reduce the cable vibration or to increase critical wind speed of the cable vibration?

Therefore, existing wind study results on cables are being examined to provide the above mentioned information useful to the bridge engineers.

3.3 Wind-induced Vibration of Girders

In ‘the Manual’, assumed bridge types were suspension bridges, cable-stayed bridges and box girder bridges. Recently in Japan, bridges with fewer plate girders have been chosen to reduce construction cost, and applied to longer span length, say, up to 100m. Torsional rigidity of plate girder bridges is much smaller than that of box girder bridges. While natural frequency ratios (f_θ/ f_h) for suspension and cable-stayed bridges are at least 2, the ratios for plate girder bridges are only 1.1-1.2. It may cause low torsional natural frequency and low critical wind speed of flutter and vortex-induced vibration. Therefore simple formula to predict torsional natural frequency of plate girder bridges are being developed to avoid plate girder bridges with poor wind resistance.

High-rise noise barriers have been often attached to highway bridges in city area in Japan. Noise barriers decrease B/d ratio, which affects aerodynamic characteristics of the bridge. Therefore applicability of the prediction formulae in 'the Manual' to the bridge with high-rise noise barriers is being examined.

Sometimes two bridges are constructed very closely to each other, which may cause buffeting problems. Wind-induced vibrations of bridge girders described in 'the Manual' are flutter, galloping, vortex-induced vibration and gust response. Therefore wind tunnel study results on the buffeting problems are being collected to inform bridge engineers of the potential wind-induced problems of bridges located closely to each other.

Amplitude of vortex-induced vibration decreases with turbulence intensity of wind and structural damping of the bridge as are shown in Eq.(6) to (10). Prediction method for turbulence intensity is described in 'the Manual'. Turbulence intensity is a function of the altitude of structure and the terrain surface roughness around the structure. Low intensity of turbulence can be predicted in sea area according to 'the Manual'. According to the recent field observation [3], however, turbulence intensity in open sea area was 0.02-0.10, which was lower than 0.12±30%, the value described in 'the Manual'. Therefore design values of turbulence intensity are being examined.

Design values of structural damping are recommended in 'the Manual' based on the full-scale vibration tests. According to the recent full-scale vibration test [4], however, structural damping of box birder bridges was 0.028-0.044, which was lower than 0.048, the value recommended in 'the Manual'. Therefore design values of structural damping are being examined.

4. CONCLUSION

In this paper, the existing Wind Resistant Design Manual for Highway Bridges was outlined first. Then some descriptions of the manual to be improved or revised were introduced. They are as follows:
(1) Formulae to predict vortex-induced vibration of A-type towers, reverse Y-type towers and single column type towers should be developed.
(2) Existing wind study results on cables should be examined to provide useful information for prediction and mitigation of rain vibration and wake galloping of cables.
(3) Simple formula to predict torsional natural frequency of plate girder bridges should be developed.
(4) Applicability of the prediction formula to the bridge with high-rise noise barriers should be examined.
(5) Wind tunnel studies on the buffeting problems of bridges located closely to each other should be collected and introduced to inform bridge engineers of the potential problems.
(6) Design values of turbulence intensity and structural damping should be examined and revised.

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Table 1 Contents of the existing Wind Resistant Design Manual for Highway Bridges and the provisions to be improved or revised

1. GENERAL REMARKS	
2. GUIDELINE OF WIND RESISTANT DESIGN	
3. DESIGN WIND LOAD	
4. WIND PROPERTIES USED IN DESIGN	**Basic Wind Speed, Design Wind Speed, Intensity of Turbulence, etc.**
5. WIND-INDUCED VIBRATIONS OF BRIDGE GIRDERS	**Prediction, Evaluation, Method of Alleviation, Flutter, Galloping, Vortex-Induced Vibrations, Gust Responses**
6. WIND-INDUCED VIBRATIONS OF TOWERS AND BRIDGE MEMBERS	**Examples of Field Observation, Examples of Wind Tunnel Study, Method of Alleviation, Galloping, Vortex-Induced Vibrations, Rain Vibrations, Wake Galloping**
7. WIND RESISTANT DESIGN AT ERECTION STAGES	**Prediction, Evaluation, Method of Alleviation, Galloping, Vortex-Induced Vibrations**
8. WIND TUNNEL TESTING METHODS	**Measurement of Steady Aerodynamic Force, Measurement of Wind-induced Vibration**

Note: The provisions to be improved or revised are underlined.

Table 2 Wind resistant design methods for bridge girders according to the Manual
and the provisions to be improved or revised

<u>a. Wind-induced vibrations to be considered</u>	**Flutter, Galloping, Vortex-Induced Vibrations, Gust Responses**
b. Verification methods	**For flutter and galloping,** $U_{cf} > U_r$ --- Flutter $U_{cg} > U_r$ --- Galloping $U_r = U_d\ E_{r1}\ E_{r2}$ $U_d = U_{10}\ E_1$ **For vortex-induced vibrations,** $U_{cv} > U_d$, or $h \leqq h_a = 0.04/f_h$ --- bending (in m) $\theta \leqq \theta_a = 2.28/(b\ f_\theta)$ --- torsion (in deg.)
c. Prediction methods **<u>c-1. Prediction by simple formulae</u>**	**For critical wind speed of flutter,** $U_{cf} = 2.5\ \underline{f}_\theta B$ **For critical wind speed of galloping,** $U_{cg} = 8\ f_h\ B$; when angle of attack is almost 0 deg $U_{cg} = 4\ f_h\ B$; when angle of attack is positive. **For critical wind speed and amplitude of vortex-induced vibrations,** $U_{cv} = 2.0\ f_h\ B$ --- bending $U_{cv} = 1.33\ \underline{f}_\theta\ B$ --- torsion $A_c = A_e\ E_{ms}\ E_t$ $A_e = \beta_{ds} \cdot 0.05 \cdot (d/B)/(m_r\ \underline{\delta}_h)$ --- bending (in h/B) $A_e = \beta_{ds} \cdot 13.2 \cdot (d/B)^3/(Ip_r\ \delta_\theta)$--- torsion (in deg.) $E_t = 1\text{-}15\ \beta_t\ (B/d)^{1/2}\underline{Iu}^2 \geqq 0$--- bending $E_t = 1\text{-}20\ \beta_t\ (B/d)^{1/2}\underline{Iu}^2 \geqq 0$--- torsion
c-2. Prediction by wind tunnel testing	**Section model test, Taut-strip model test, Full model test**
d. Countermeasures	**Improvement of cross sectional shape** **Increase of damping capacity**

Note: The provisions to be improved or revised are underlined.

Table 3 Wind resistant design methods for towers according to the Manual
and the provisions to be improved or revised

a. Wind-induced vibrations to be considered	Galloping, Vortex-Induced Vibrations
b. Verification methods	For galloping, $U_{cg} > U_r$ --- Galloping $U_r = U_d E_{r1} E_{r2}$ $U_d = U_{10} E_1$ For vortex-induced vibrations, $U_{cv} > U_d$, or $h \leqq h_a$
c. Prediction methods c-1. Prediction by simple formulae	For critical wind speed and amplitude of vortex-induced vibrations of twin parallel column type towers, $U_{cv} = 10 f_1 D_T$ $h_{max}/D_T = 4 \rho D_T^2 / (m_{eq} \delta_s)$
c-2. Prediction by wind tunnel testing	Rigid model test, Elastic model test
d. Countermeasures	Increase of damping capacity Improvement of cross sectional shape

Note: The provisions to be improved or revised are underlined.

Table 4 Wind resistant design methods for cables according to the Manual
and the provisions to be improved or revised

a. Wind-induced vibrations to be considered	Vortex-Induced Vibrations, Rain Vibrations, Wake Galloping
b. Verification methods	
c. Prediction methods	Prediction by wind tunnel testing
d. Countermeasures	Increase of damping capacity Connecting with an adjacent cable

Note: The provisions to be improved or revised are underlined.