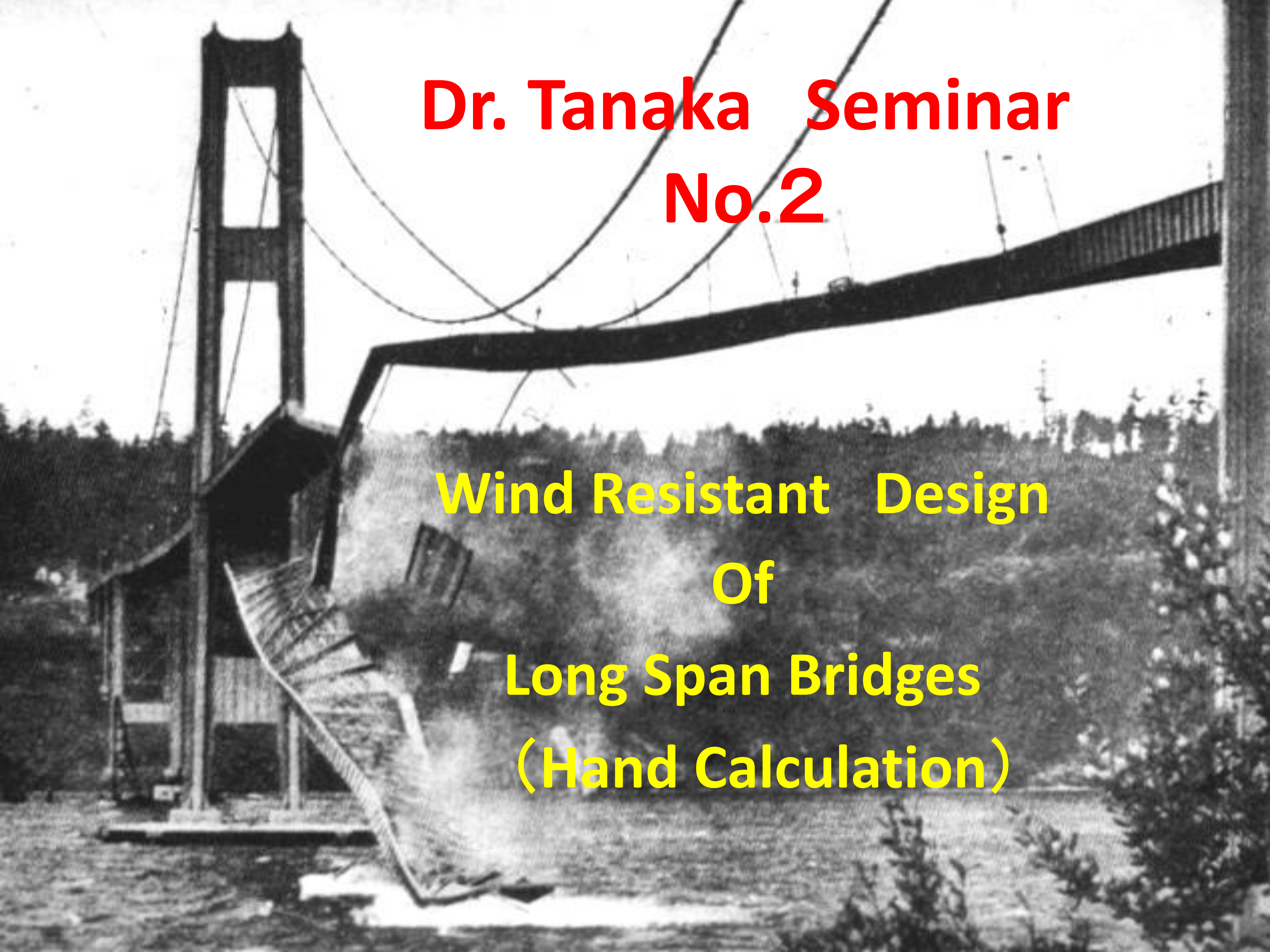


Dr. Tanaka Seminar No.2

Wind Resistant Design Of Long Span Bridges (Hand Calculation)

Contents

1. Harmful Vibrations

- Flutter
- Flutter Design Wind Velocity（Vcr）
  （Completion & Erection）
- Galloping

・Galloping Design Wind Velocity（Vgcr）
（Completion & Erection）

Vortex Shedding

- Vortex Shedding Velocity
- Amplitude of Vortex Shedding
- Meiko　Nishi　Bridge　／　3D-Wind Tunnel

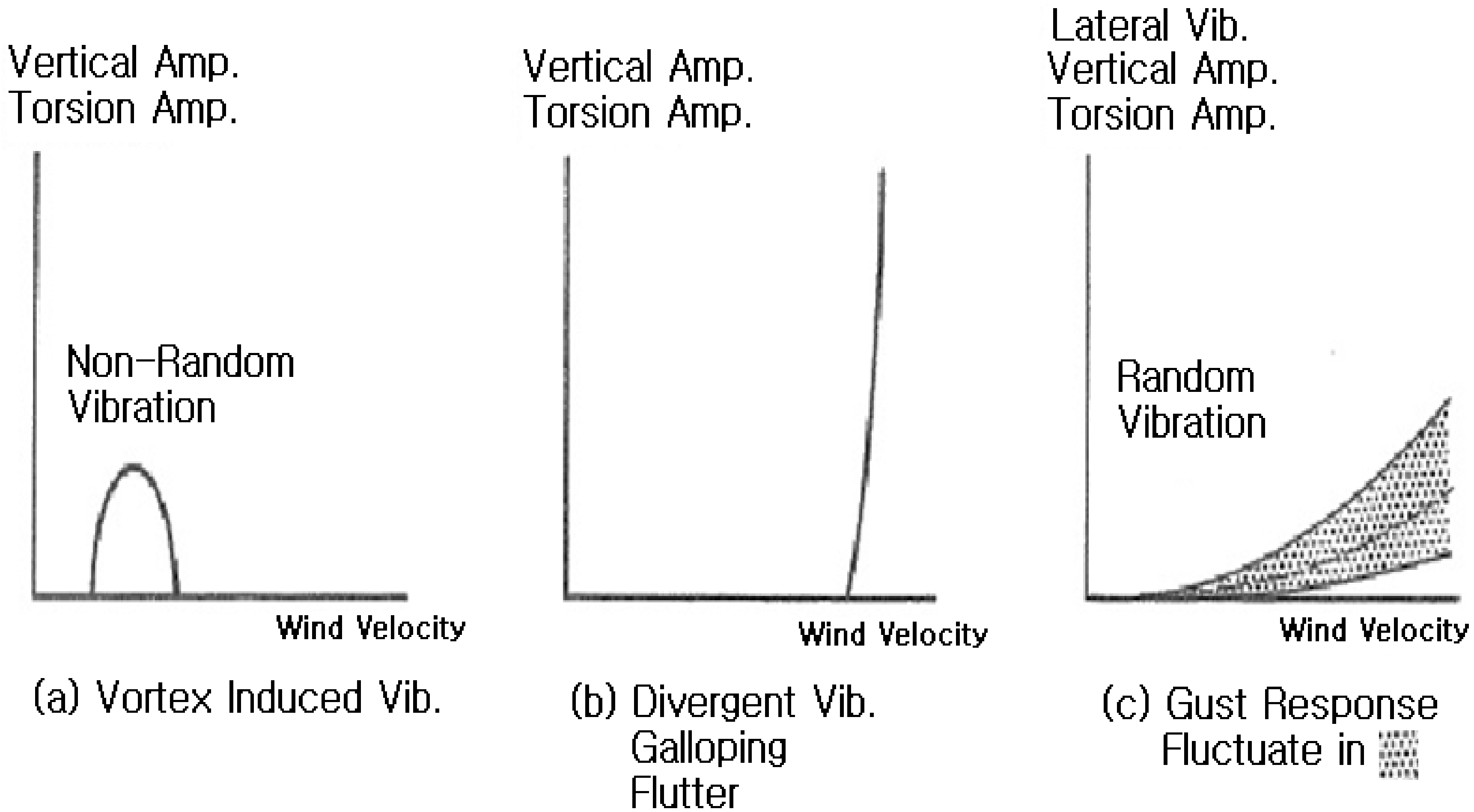
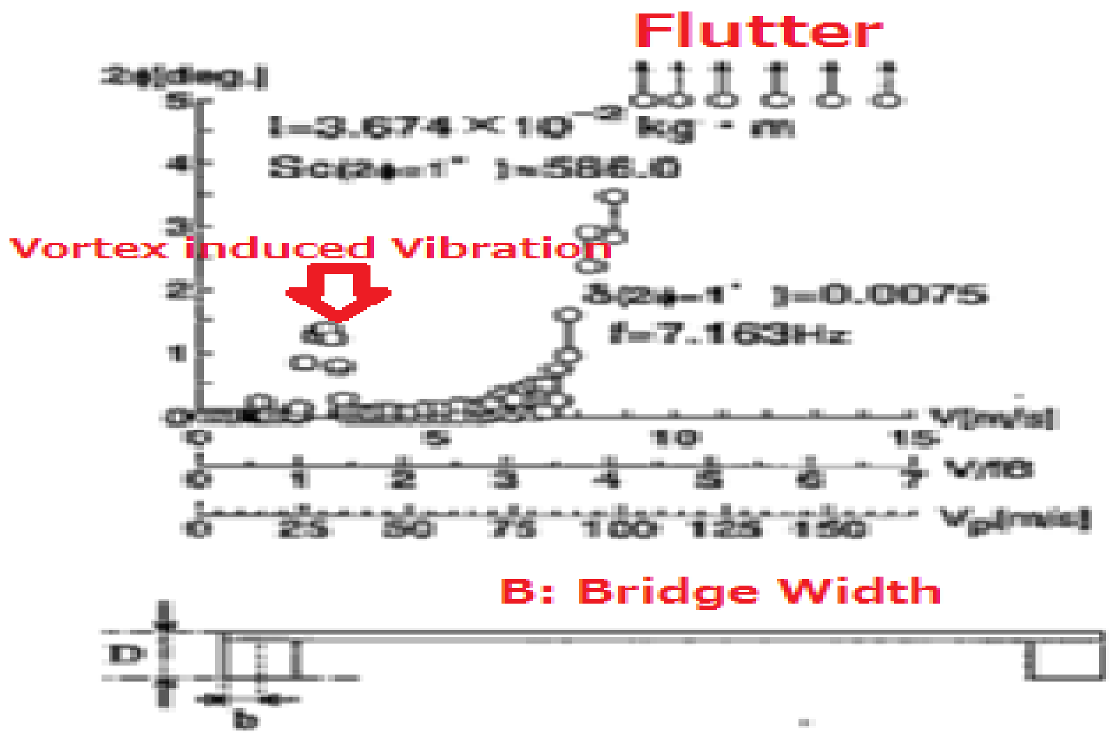


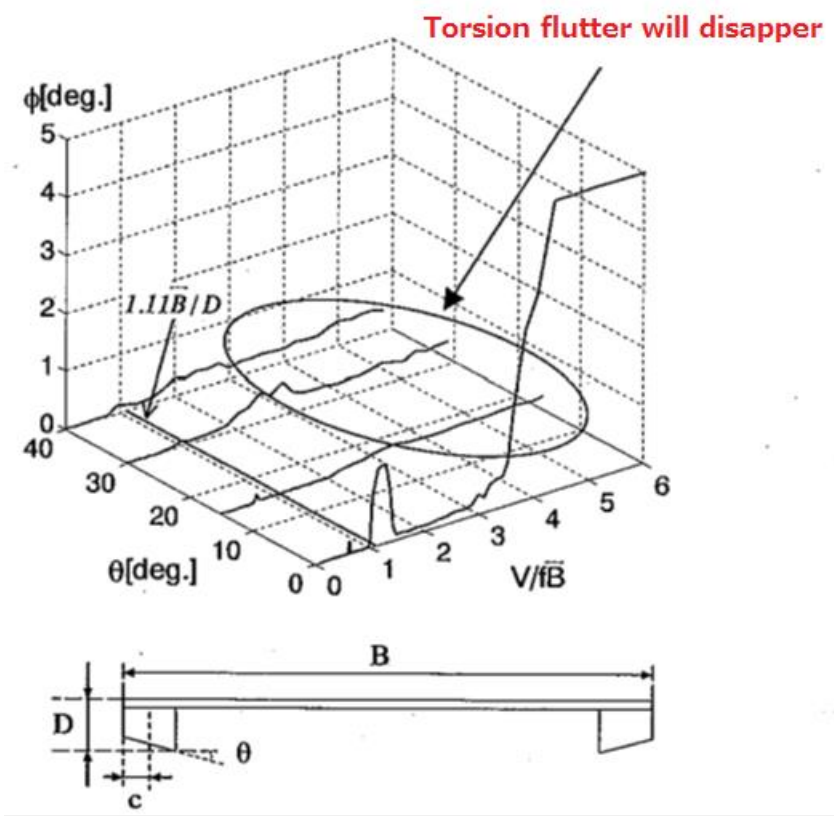
Fig.-1 Phenomenon Induced by Winds

Bad Deck Configuration



Box Section (B/D=10)

Good Deck Configuration



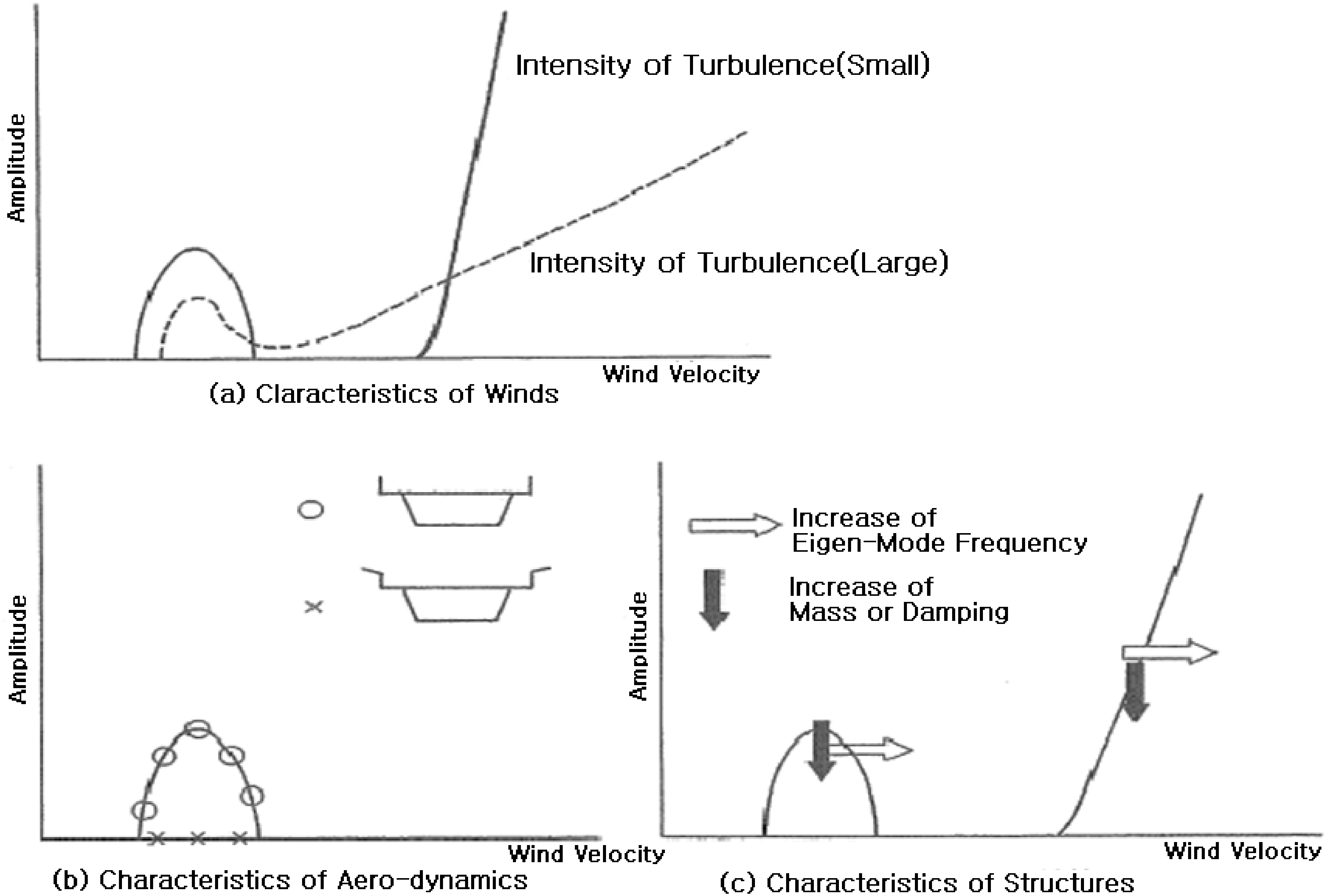


Fig.-2 Structural Responses by Wind Effects

Table-1 Relationship between Bridge Type & Wind Vibration

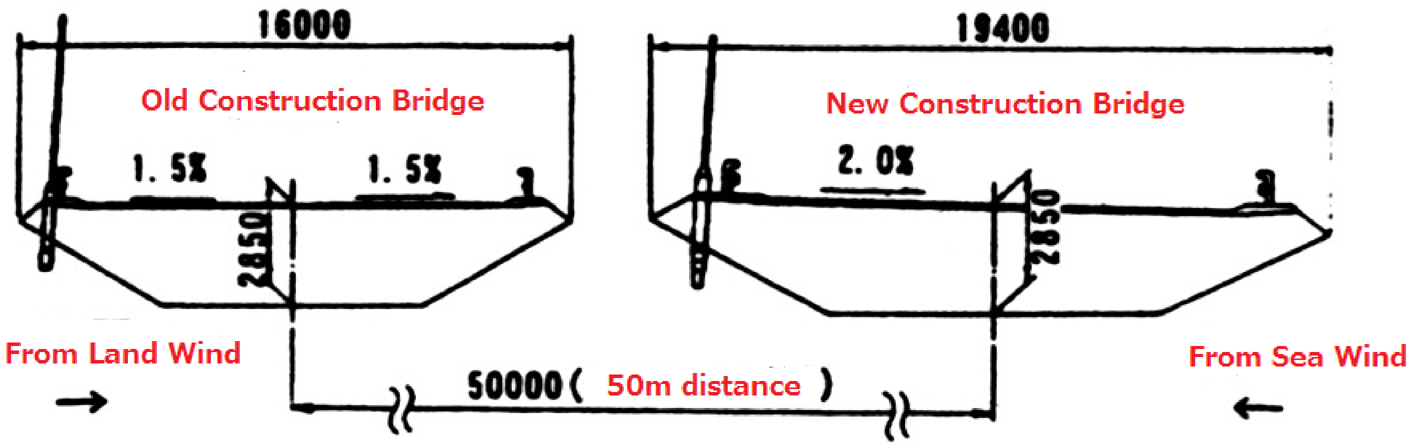
Phenomenon / Bridge Type			Divergent Vibration		Vortex Shedding Vibration	
			Vertical	Torsion	Vertical	Torsion
Suspension Br. / Cable-Stayed Br.	Truss		X	○	X	X
	Box Girder	Steel	○	○	○	○
		Concrete	X	○	○	○
Steel Deck Br.	Box Girder		○	X	○	X
	I Girder		○	○	○	○

○ : Wind Resistant Design is necessary.
X : Wind Resistant Design is not necessary.

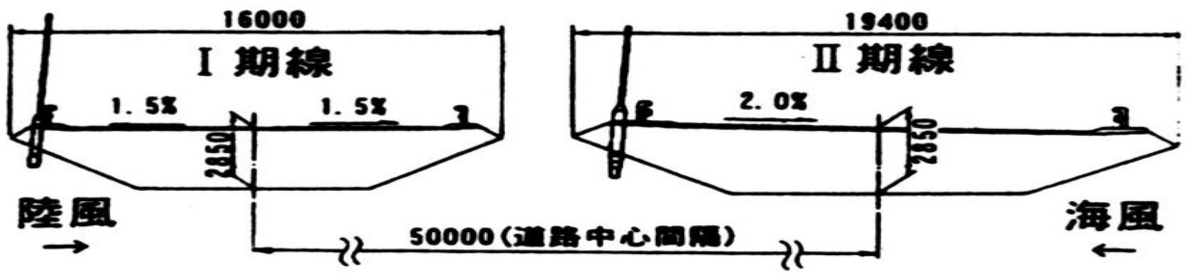
Parallel   Cable Stayed Bridges

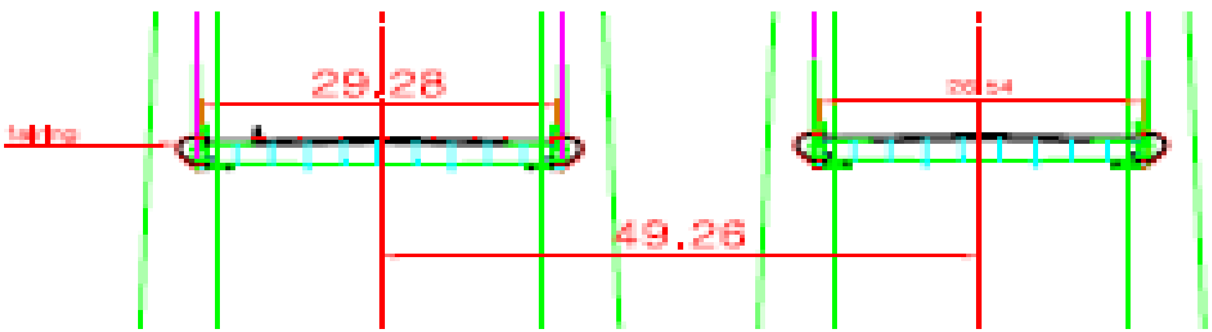
The Meiko Nishi Bridge

Twin Section



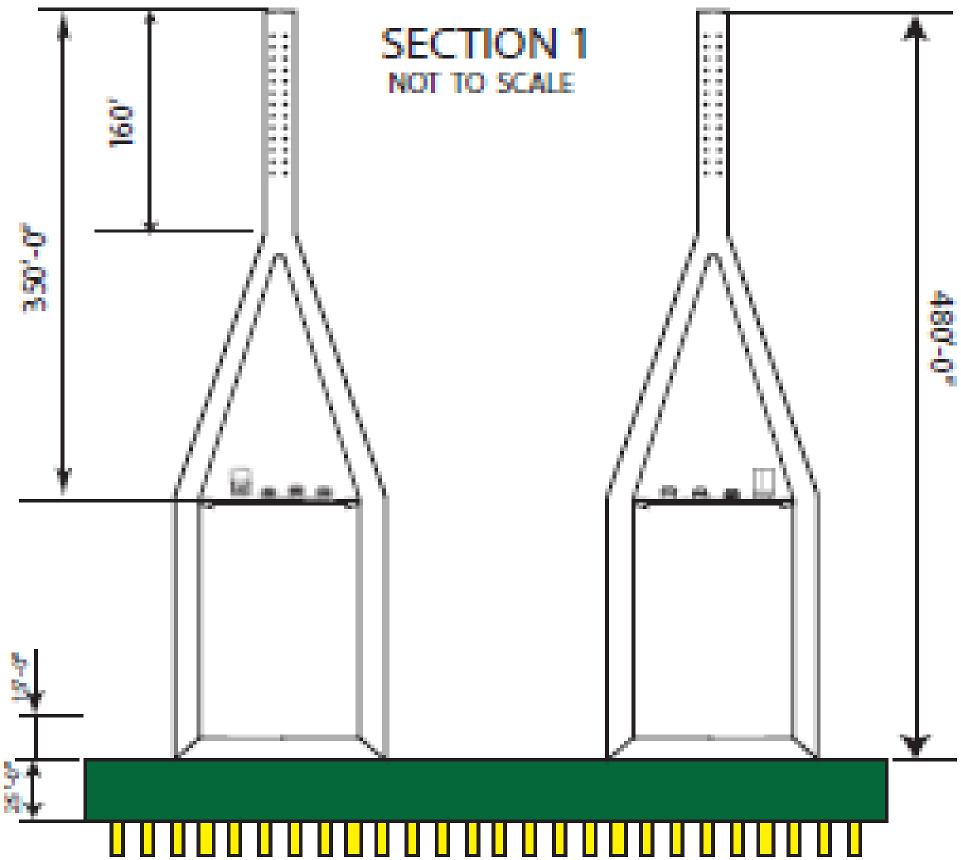
Simple comparison between USA bridge and Meiko Nishi Br.





Tower aerodynamics

- Tower's aero-dynamical interfere may happen. Research is necessary.



Why parallel cable-stayed bridge is difficult to predict wind stability?

- Wind flow is complex because wind and bridge interfere with each other.
- Even if we do wind tunnel experiments, we sometimes can not find good solutions.
- In that case, TMD (tuned mass damper) is necessary.
- Now we do not have good general solution to parallel cable-stayed bridge on aerodynamics.

Cable Vibration

- **Cable vibration is also very complex therefore I will give you lectures at another occasion.**

Rain Vibration Happened
2p.m.14th July 2009 at site.

2. Checking Harmful Vibrations

- **(1) Simple Eigen Value Calculation**
- **(2) Flutter Velocity**
- **(3) Galloping Velocity**
- **(4) Vortex Shedding Velocity**

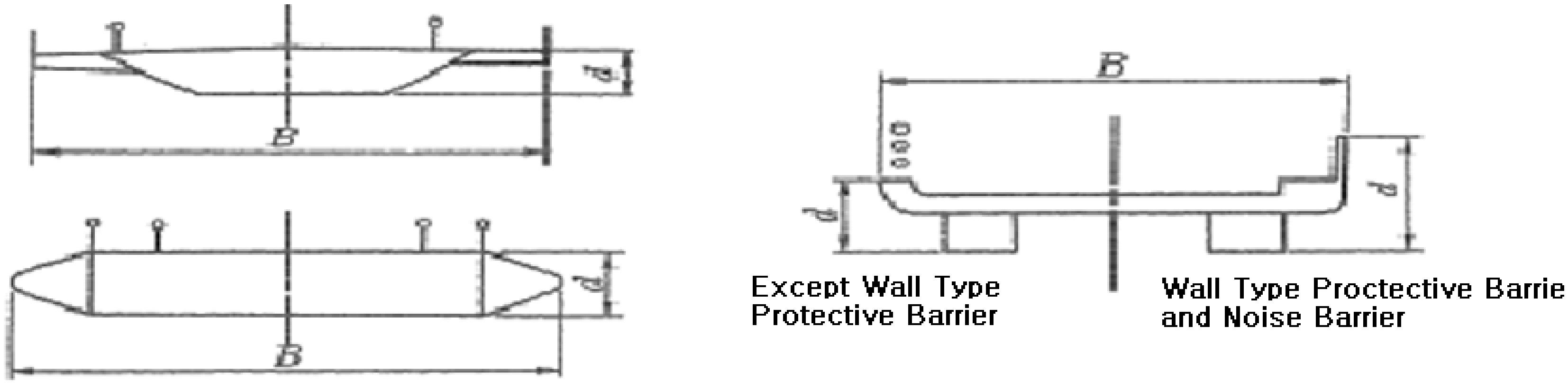
Simple Eigen Value Calculation

- **(1) First Vertical Vibration(f_h)**
- f_h = 100 / L (L : Span Length(m)) …(5.4)
- = 100/366 = 0.27Hz
- **(2) First Torsion Vibration(f_ϑ)**
- f_ϑ = 3 f_h （Box Deck） ....(5.6)
- = 3 × 0.27 = 0.82Hz
- **NB. The number of Equations are from Dr. Tanaka's paper of KSSC**

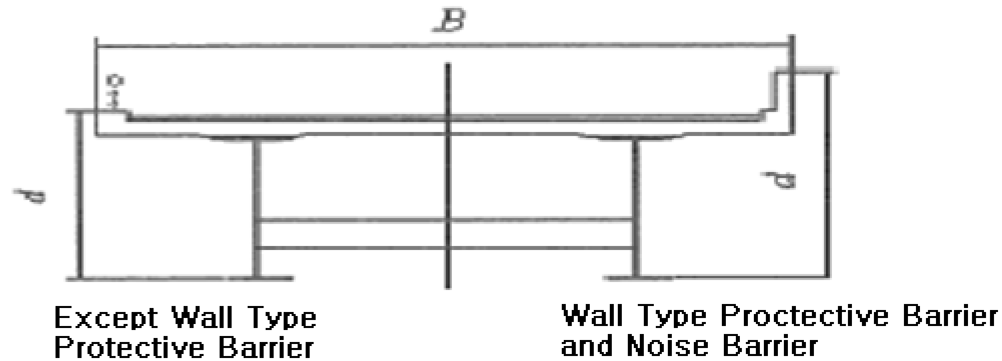
Flutter Velocity(U_{ct})

- **Flutter Velocity(U_{ct}) is as follows:**
- $U_{cf} = 2.5 \ f_{\vartheta} \cdot B$ .... (5.8)
- $= 2.5 \times 0.82 \times 33.18$
- $= 68$m/s

- B （Deck Width）＝ 33.18 m （USA Br.）



(b) Box Type Section



(c) I Type Section

R1- Effective height(d) includes wall type handrail ,noise barrier, kerb and includes central reserve. Steel made handrail or half wall handrail(d) includes upper bound height of kerb or wall handrail.

R2- Cross slope of deck is negligible.

Fig.-3 Total Width *B* & Effective Height *d*

① Standard Design Wind Speed U_d

- Where B = 33.18m(Bridge Width)
- The site of USA Bridge is suburbs of New York. This may be almost equivalent of semi strong area in Korea.
- U_{10} = 35m/s
- Compensating Rate (E_1) is 1.1
- $U_d = U_{10} \times E_1 = 35 \times 1.1 =$ **38.5 m/s**

Table-2 Compensating Values (E_{r1}) by Fluctuation of Natural Wind

Terrain Roughness	0	Ⅰ	Ⅱ	Ⅲ	Ⅳ
E_{r1}	1.10	1.10	1.15	1.20	1.25

② Flutter Reference Velocity (U_{rf})

- $U_{rf} = 1.2Er_1 \times U_d$ ……………… （5.2）
- **Terrain Roughness of USA Bridge is supposed to be Ⅱ, then E_{r1} = 1.15**
- U_{rf} ＝ 1.2 × 1.15 × 38.5 = 53 m/s
- **以上より、**
- **Ucf = 68 m/s > U_{rf} = 53 m/s**
- **Flutter is no problem.**

Terrain　Ⅰ

（b）　地表粗度区分 I

Terrain Ⅱ

（c） 地表粗度区分 II

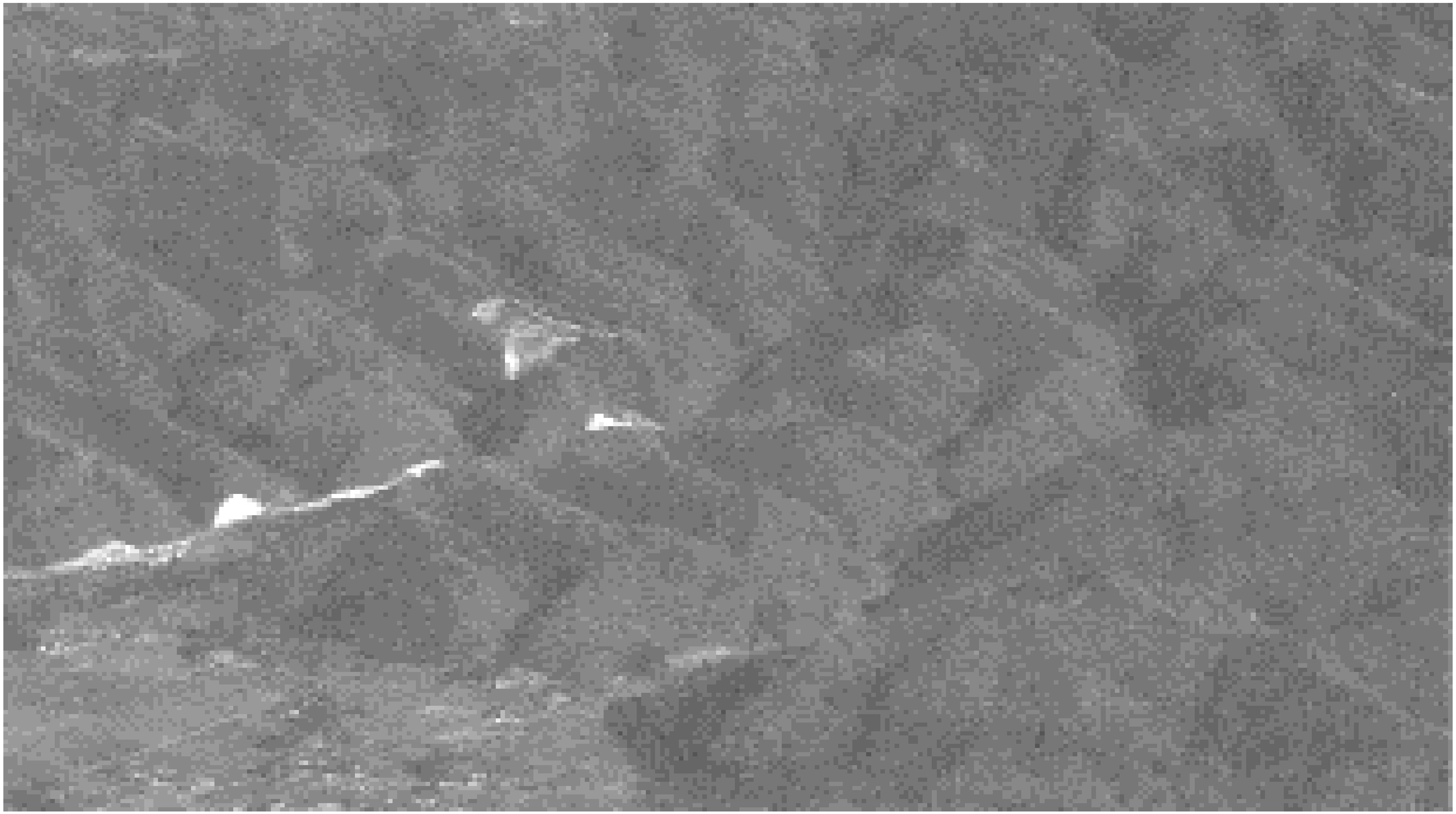
Terrain Ⅲ

(d) 地表粗度区分図

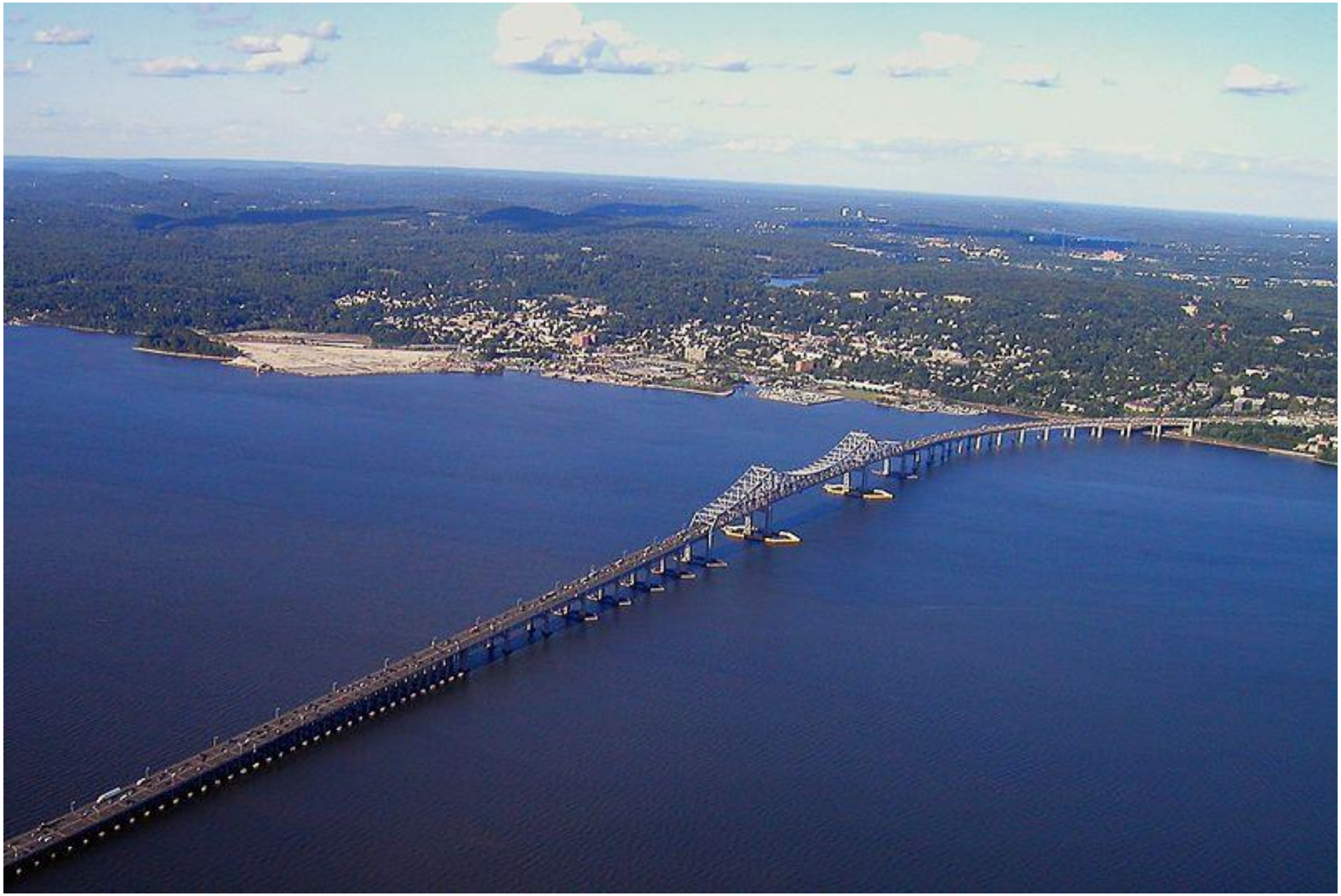
Terrain Ⅳ

（e） 地表粗度区分Ⅳ

Terrain V



USA Bridge （Terrain Ⅱ）



Check of Galloping
（1） Galloping Velocity（U_{cg} ）

- $U_{cg} = 8 f_h \cdot B$ （where steel bearing）（5.13）
- $= 8 \times 0.27 \times 33.18$
- $=$ 72 m/s
- $U_{cg} = 4.5 f_h \cdot B$（where rubber bearing）(5.14）
- $=$ 40 m/s

(2) Galloping Checking Velocity (U_{rg})

- $U_{rg} = 1.2 \times U_d$ .... (5.12)
- $= 1.2 \times 38.5$
- $= 46$ m/s
- (i) Steel Bearing
- $U_{cg} = 72$ m/s $>$ $U_{rg} = 46$ m/s → OK
- (ii) Rubber Bearing
- $U_{cg} = 40$ m/s $<$ $U_{rg} = 46$ m/s → NG

We must be careful to use rubber bearing.

Check of Vortex Shedding

- （3）**Vertical Vibration of Vortex Shedding**
- ① **Vortex Shedding Velocity（U_{cvh} ）**
- U_{cvh} = 2.0 f_h ･ B ....（5.19）
- = 2.0 × 0.27 x 33.18
- = 18 m/s

② Calculation of Amplitude（h_c ）

- h_c = $h_e \cdot E_{ms} \cdot E_{th}$ ....（5.21）
- $h_e = \beta_h \cdot B /(m_r \cdot \delta_h)$ ....（5.22）
- E_{ms} = 1.3 （Conventional Number）
- β_h ＝0.05 $(B/d)^{-1} \cdot \beta_{ds}$ ....（5.24）
- $(B/d)^{-1}$ = $(33.18/2.8)^{-1}$ = 0.084
- β_{ds} = 1 （Section is almost hexagonal）
- Then、 β_h ＝0.05 x 0.084 x 1 = 0.0042

Hexagonal Deck

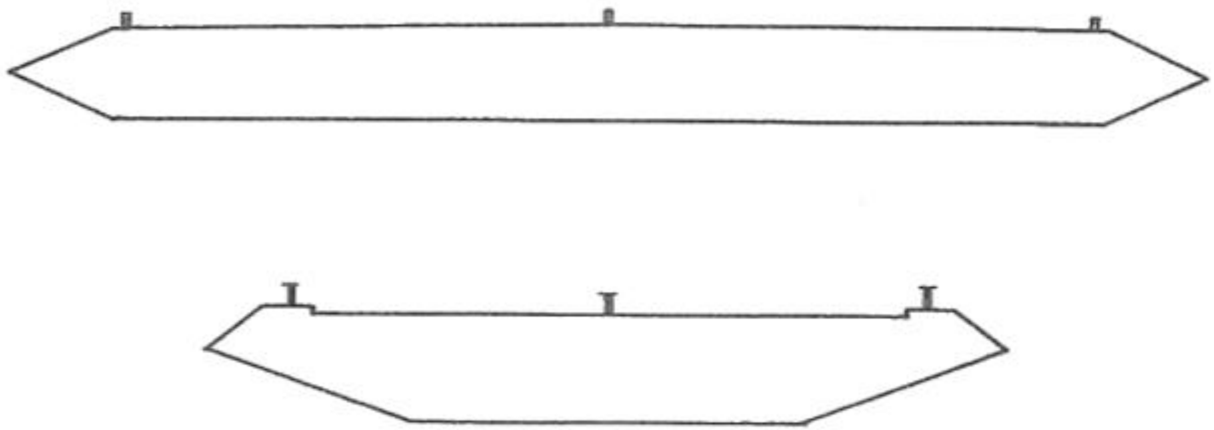


Fig.-5 Example of Hexagonal Deck

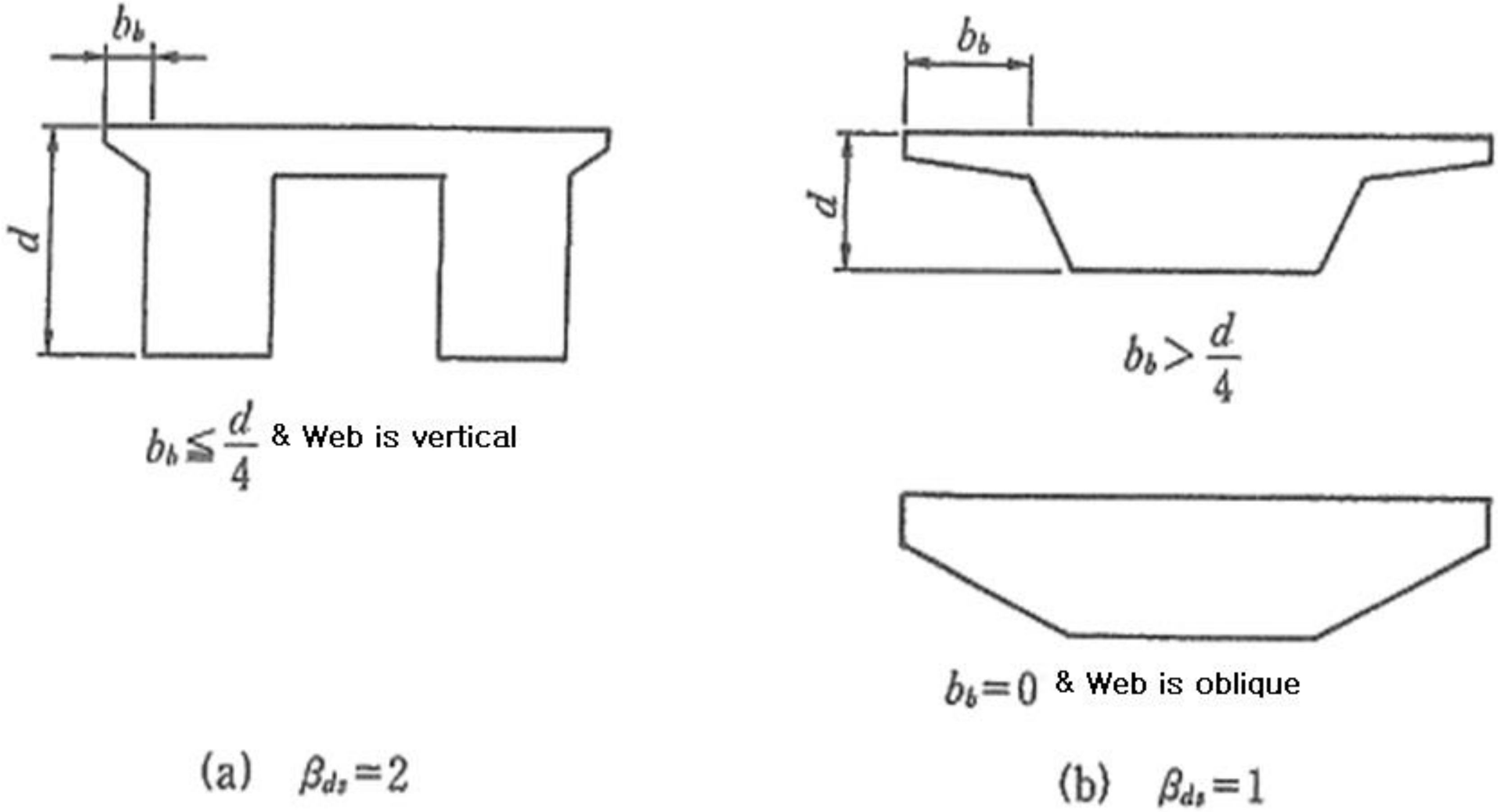


Fig.-4 Compensating Rate on Deck Shapes

Table-2 Structural Damping (Logarithmic Decrement)

Type of Bridges		Structural Damping δ
Suspension Br.	Truss Girder	0.03
	Box Girder	0.02
Cable-stayed Br.	Truss Girder	0.03
	Box Girder	0.02
Girder Br.	Steel Shoe	$\frac{0.75}{\sqrt{L}}$
	Rubber Shoe	$\frac{0.35}{\sqrt{L}}$

Where, L is Maximum span(m)

NB) If vibration control devices are install, you must consider their effect.

Table-3 Amplitude Reduction Rate of Vortex Induced Vib.(E_{th})

<table>
<tr><th rowspan="2">I_u / B/d</th><th colspan="10">Except Hexagonal Deck</th><th rowspan="2">Hexagonal Deck</th></tr>
<tr><th>0.11</th><th>0.12</th><th>0.13</th><th>0.14</th><th>0.15</th><th>0.16</th><th>0.17</th><th>0.18</th><th>0.19</th><th>0.20</th></tr>
<tr><td>$2 < B/d \leqq 3$</td><td colspan="2">0.7</td><td colspan="2"></td><td>0.5</td><td colspan="2">0.4</td><td>0.3</td><td>0.2</td><td>0.1</td><td rowspan="9">1</td></tr>
<tr><td>$3 < B/d \leqq 4$</td><td></td><td colspan="2">0.6</td><td>0.5</td><td>0.4</td><td>0.3</td><td>0.2</td><td>0.1</td><td colspan="2"></td></tr>
<tr><td>$4 < B/d \leqq 5$</td><td colspan="2"></td><td></td><td rowspan="2">0.4</td><td rowspan="2">0.3</td><td rowspan="2">0.2</td><td>0.1</td><td colspan="3"></td></tr>
<tr><td>$5 < B/d \leqq 6$</td><td rowspan="2"></td><td colspan="2"></td><td colspan="4" rowspan="2"></td></tr>
<tr><td>$6 < B/d \leqq 7$</td><td></td><td rowspan="2">0.4</td><td rowspan="2">0.3</td><td>0.2</td><td>0.1</td></tr>
<tr><td>$7 < B/d \leqq 8$</td><td colspan="2">0.5</td><td rowspan="2">0.1</td><td colspan="5" rowspan="2">0</td></tr>
<tr><td>$8 < B/d \leqq 9$</td><td rowspan="3"></td><td rowspan="3">0.4</td><td rowspan="2">0.3</td><td rowspan="2">0.2</td></tr>
<tr><td>$9 < B/d \leqq 10$</td><td colspan="6" rowspan="2"></td></tr>
<tr><td>$10 < B/d \leqq 11$</td><td>0.2</td><td>0.1</td></tr>
</table>

Table-4 Amplitude Reduction Rate of Vortex Induced Vib. ($E_{t\theta}$)

<table>
<tr><th rowspan="2">I_w / B/d</th><th colspan="10">Except Hexagonal Deck</th><th rowspan="2">Hexagonal Deck</th></tr>
<tr><th>0.11</th><th>0.12</th><th>0.13</th><th>0.14</th><th>0.15</th><th>0.16</th><th>0.17</th><th>0.18</th><th>0.19</th><th>0.20</th></tr>
<tr><td>$2 < B/d \leqq 3$</td><td>0.7</td><td>0.6</td><td>0.5</td><td>0.4</td><td>0.3</td><td>0.2</td><td>0.1</td><td></td><td></td><td></td><td rowspan="9">1</td></tr>
<tr><td>$3 < B/d \leqq 4$</td><td>0.6</td><td>0.5</td><td>0.4</td><td>0.3</td><td>0.2</td><td>0.1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>$4 < B/d \leqq 5$</td><td rowspan="2">0.5</td><td rowspan="2">0.4</td><td rowspan="2">0.3</td><td>0.2</td><td>0.1</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$5 < B/d \leqq 6$</td><td rowspan="2">0.1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$6 < B/d \leqq 7$</td><td rowspan="3">0.4</td><td rowspan="2">0.3</td><td>0.2</td><td></td><td></td><td></td><td>0</td><td></td><td></td></tr>
<tr><td>$7 < B/d \leqq 8$</td><td rowspan="2">0.1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$8 < B/d \leqq 9$</td><td rowspan="2">0.2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$9 < B/d \leqq 10$</td><td rowspan="2">0.3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$10 < B/d \leqq 11$</td><td>0.1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

- New York Area : Intensity of Turbulence
  is Iu = 0.11 (assumption)
- From Table-3: E_{th} = 0.5
- m_r : Non Dimensional Mass（$=m/(\rho B^2)$）
- Edge Girder Deck（Option 1）
- Concrete Deck （Option 2）

- (i) **Amplitude of Edge Girder（Option 1）**
- m = 31.094（Deck）+ 680/2/366 = 32 t/m
- m_r = 32 x 10^3 /(1.23 x 33.18^2) = 23.6
- h_e = 0.0042 x 33.18/(23.6 x 0.02) = 0.30 m
- Then h_c = $h_e \cdot E_{ms} \cdot E_{th}$ = 0.30 x 1.3 x 0.5
- = **0.20 m**
- (ii) **Amplitude of Concrete Deck（Option2）**
- Same procedure of Option 1
- h_c = $h_e \cdot E_{ms} \cdot E_{th}$ = 0.15 x 1.3 x 0.5 = **0.10 m**

③ Conclusion

- We must be careful that there is possibility as follows;
- At wind velocity **18m/s**
- **Edge girder** will vibrate at amplitude **20 cm**.
- **Concrete deck** will vibrate at amplitude **10 cm**.
- **It is necessary to check that these amplitude is harmful to the railway loads.**

Vortex Shedding Torsion

- ① **Vortex Shedding Velocity** ($U_{cv\vartheta}$)
- $U_{cv\vartheta}$ = 1.33 ･ f_{ϑ} ･ B ……………….(5.29)
  = 1.33 x 0.82 x 33.18
  = **36 m/s**
- ② **Calculation of Amplitude** (h_c)
- ϑ_c = ϑ_e ･ E_{ms} ･ $E_{t\vartheta}$ ……………….(5.32)
- ϑ_e = β_{ϑ} / (I_{pr} ･ δ_{ϑ}) ………………. (5.33)

- E_{ms} = 1.3 （Conventional Value）
- $\beta_h = 13.2 \ (B/d)^{-3} \cdot \beta_{ds}$ …………（5.24）
- $(B/d)^{-3}$ = $(33.18/2.8)^{-3}$ = 0.0006
- β_{ds} = 1 （ Section is almost hexagonal ）
- Then
- $\beta_{\vartheta} = 13.2 \times 0.006 \times 1 = 0.008$

$$E_{ms} = \frac{\int_D \Phi^2 dx}{\int_D |\Phi| \Phi^2 dx} \quad \cdots\cdots \quad (5.40)$$

Where, $\int_D dx$: Integral on Decks

Φ : Vertical or Torsional Vibration Mode

NB. If you count on similitude of vibration mode by wind tunnel tests, Ems=1

- β_{ds} = 1 （Section is almost hexagonal）
- Then
- β_{ϑ} ＝13.2 x 0.006 x 1 = 0.008

- New York Area : Intensity of Turbulence

  is Iu = 0.11 (assumption)
- Then $E_{t\vartheta}$ = 0.3 （Table-4）
- I_{pr} : Non dimensional moment inertia

（=$I_p/(\rho B^4)$

We will calculate Option 1 and Option 2 separately.

- Where I_p ＝（$0.3B$）^{2} ・m ……………… （5.37）

(ⅰ)Amplitude of Edge Girder（Option 1）

- I_p = $(0.3B)^2 \cdot m$ = （0.3x33.18）^{2} x 32
- = 3171 tm^4/m
- I_{pr} = 3171 x 10^3 /(1.23 x 33.18^4) = 2.13
- ϑ_e = 0.008/(2.13 x 0.02) = 0.19 Degree
- Then h_c = $\vartheta_e \cdot E_{ms} \cdot E_{th}$ = 0.19 x 1.3 x 0.5
  = **0.07 Degree**
- (ii) Concrete deck（（Option 2）
- Same procedure of Option 1
- ϑ_c = $\vartheta_e \cdot E_{ms} \cdot E_{th}$ = 0.097 x 1.3 x 0.5
- = **0.04 Degree**

③ Conclusion

- At the wind velocity 36m/s, Torsional amplitude:
- Edge Girder: **0.07 Degree**
- Concrete Deck:**0.04 Degree**
- **Amplitudes are very small**
- **Therefore the vibrations are not harmful to cars and railways.**

3. Conclusions

The results are summarized as follows:

- **Flutter is not problem.**
- **Galloping is not problem with steal bearing use.**
- **Galloping is problem with rubber bearing use.**
- **Vortex shedding:**
- **Vertical vibration needs check of movability of railway**
- **Torsional vibration is not harmful.**

APPENDEX

- My explanation is intentionally to avoid height of bridge.
- I will add the wind profile information here after.
- Strictly   speaking, we must consider the height of
  Bridge.
  Then for example, the flutter reference velocity should be
  considered at deck height.
  If the deck height is 40m and terrain Ⅱ, flutter reference velocity:
  V10x(40/10)*0.12 = 53 x 1.18= 63 m/s

Correction by Height

$$\frac{U_d}{U_G} = \begin{cases} \left(\frac{z_b}{z_G}\right)^{\alpha}, & z \leqq z_b \\ \left(\frac{z}{z_G}\right)^{\alpha}, & z_b < z \leqq z_G \\ 1, & z_G < z \end{cases} \quad \cdots\cdots\cdots \quad (4.2)$$

where

U_d: design basic velocity

U_G: Wind velocity where roughness of surface does not affect

z_b: Representative height of surface

α: Power Index

Model of Wind Profile