Wind Resistant Design of Long Span Bridges

No.2

--Check of Vibrations --

Sungkyunkwan University

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Concurrent Prof.

Hiroshi TANAKA

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1. Harmful Vibrations

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  （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

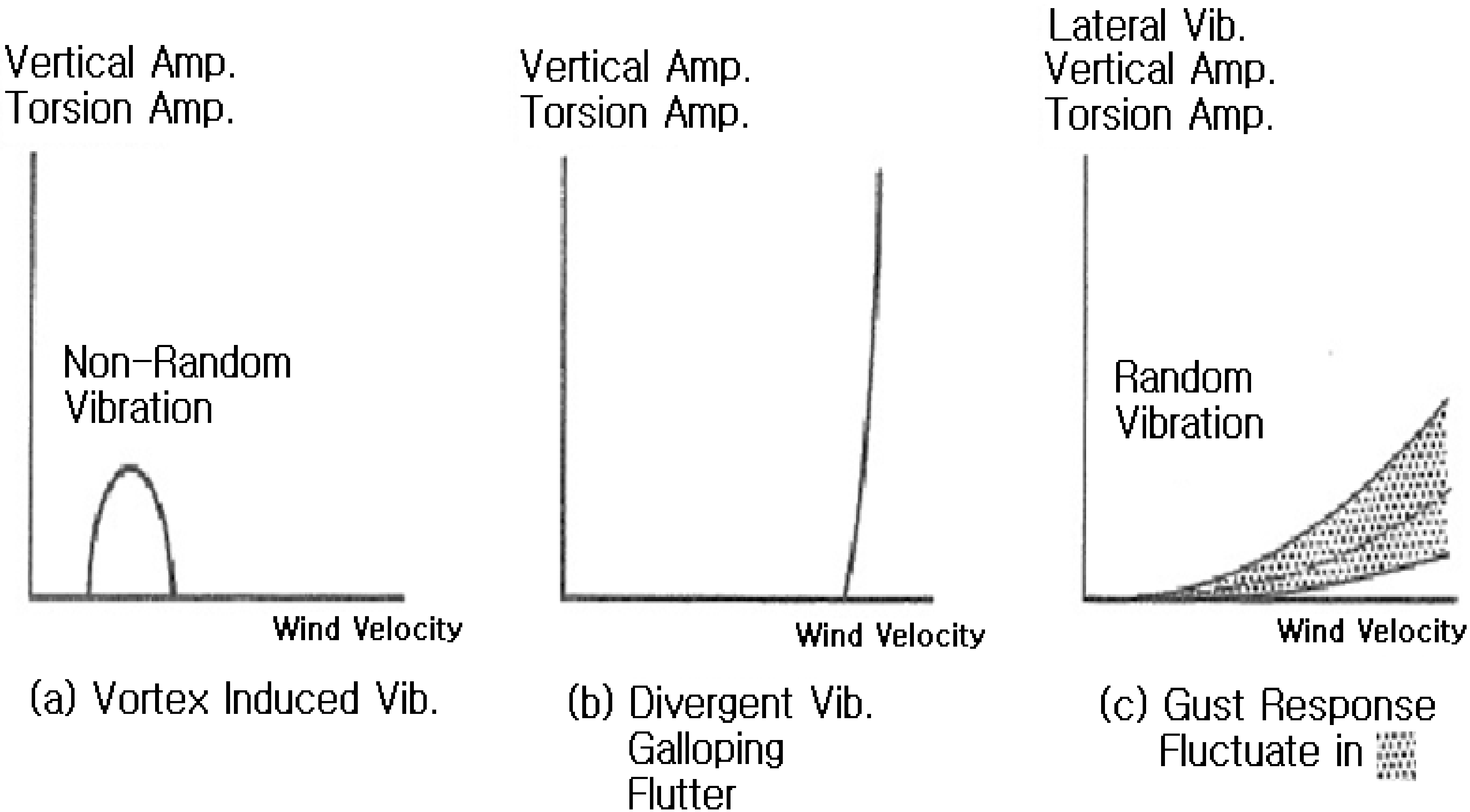
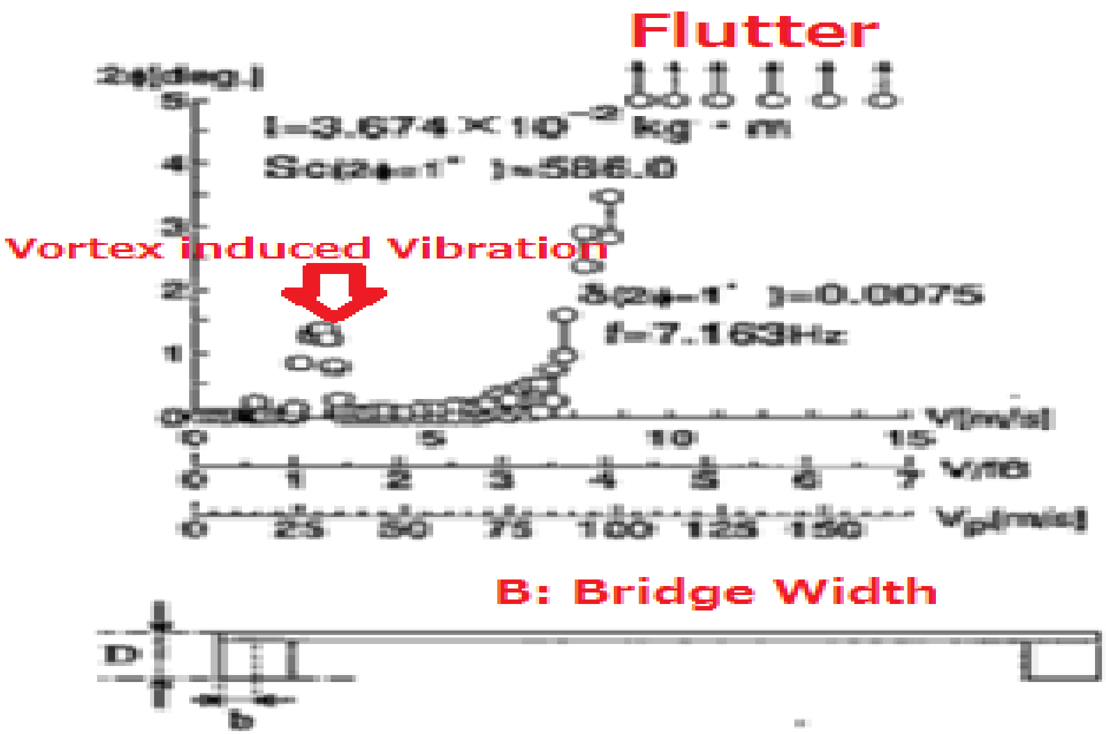


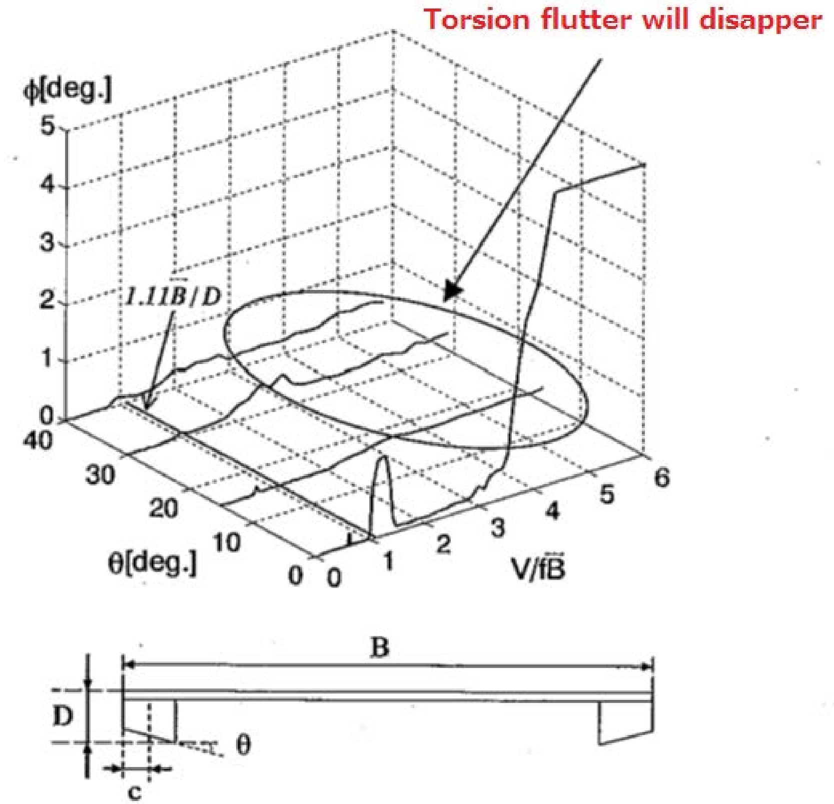
Fig.-1 Phenomenon Induced by Winds

Bad Deck Configuration



Box Section (B/D=10)

Good Deck Configuration



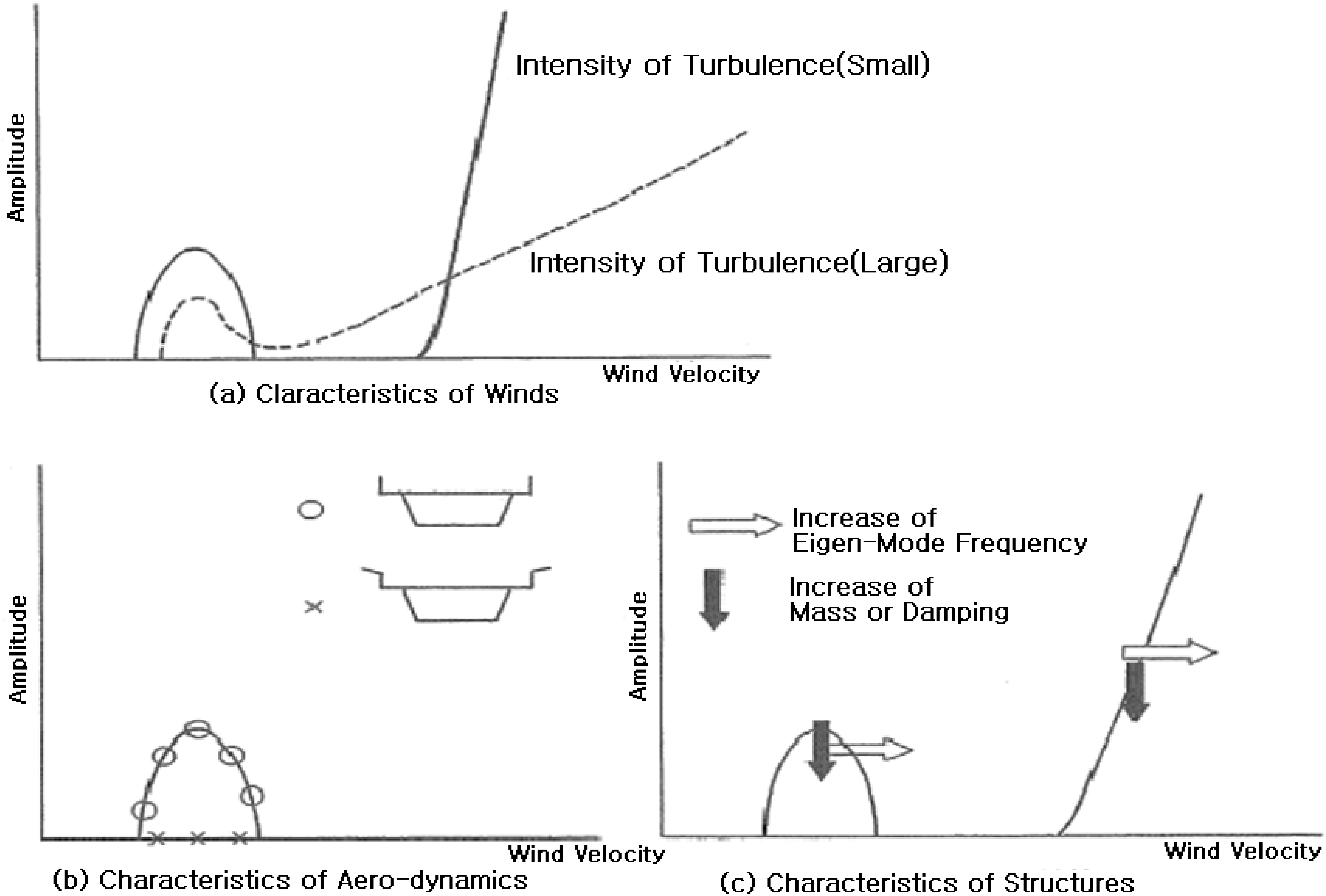


Fig.-2 Structural Responses by Wind Effects

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Table-1 Relationship between Bridge Type & Wind Vibration

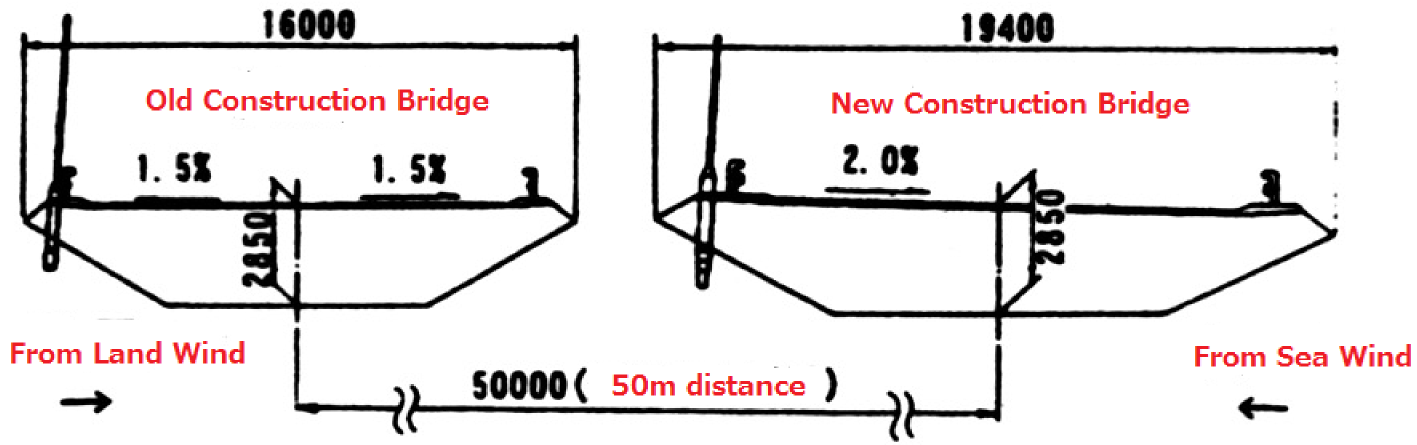
Phenomenon / Bridge Type			Divergent Vibration		Vortex Shedding Vibration	
			Vertical	Torsion	Vertical	Torsion
Suspension Br. Cable-Stayed Br.	Truss		X	○	X	X
	Box Girder	Steel	○	○	○	○
		Concrete	X	○	○	○
Steel Deck Br.	Box Girder		○	X	○	X
	I Girder		○	○	○	○

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

Parallel　Cable Stayed Bridges

The Meiko Nishi Bridge

Twin Section



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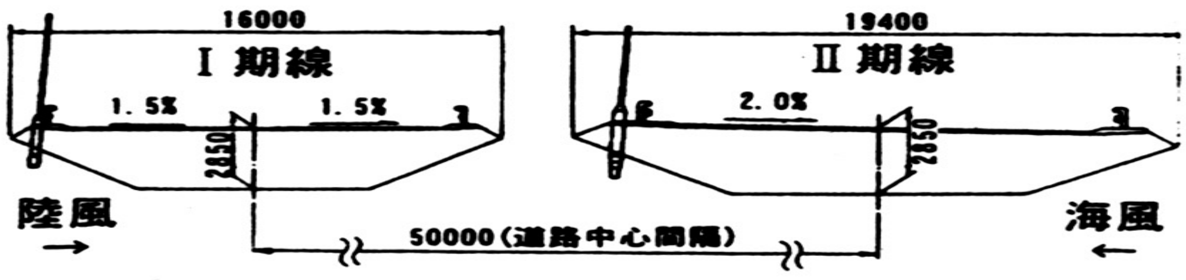
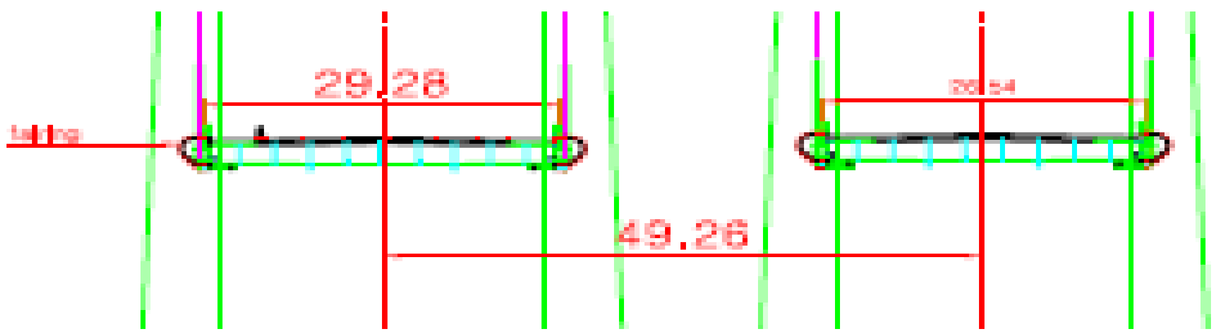
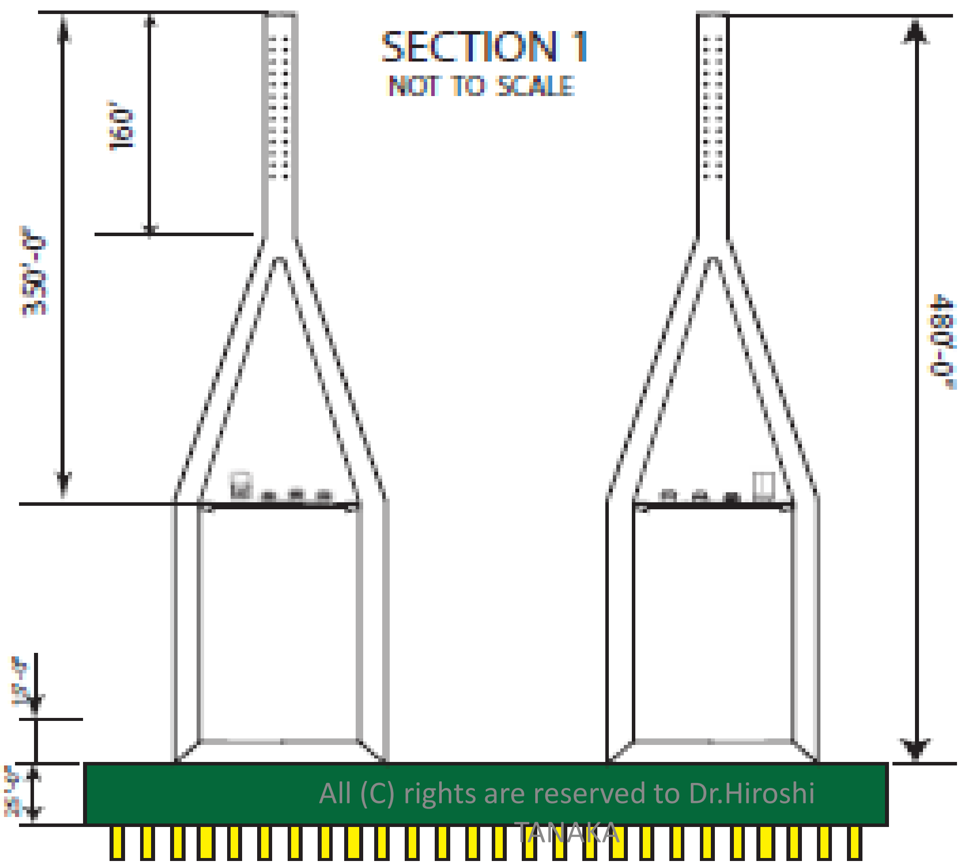
Simple comparison between USA bridge and Meiko Nishi Br.





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.

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Cable Vibration

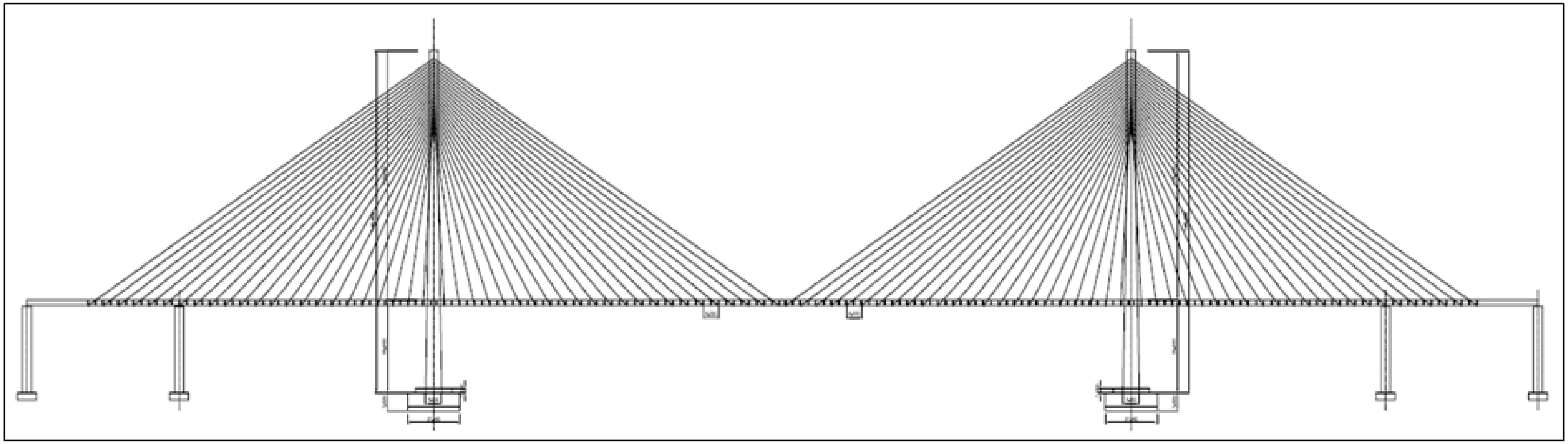
- **Cable vibration is also very complex therefore I will give you lectures at another occasion.**

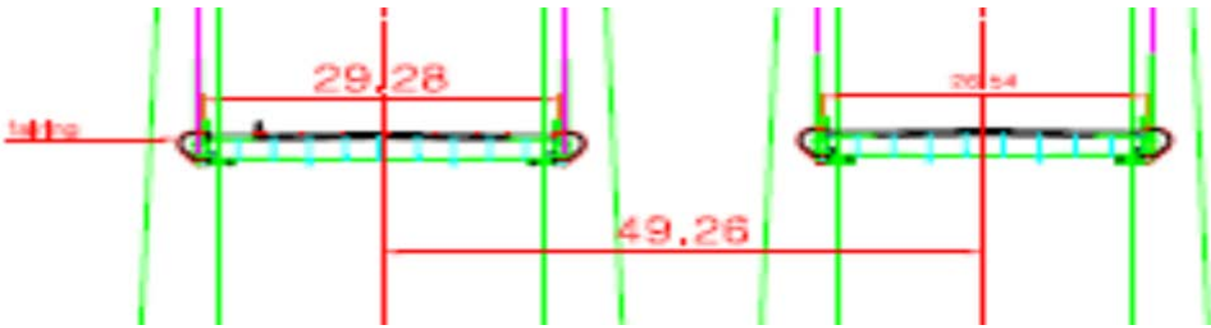
Rain Vibration Happened
2p.m.14th July 2009 at site.

2. Checking Harmful Vibrations

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

Calculation Model





- Twin bridge but we will consider single bridge.
- Center span (L) : 366m (1200ft)
- Girder Deck: Box (Not I-Girder) Type,   Width (B) 33.18 m ,   Height (d) 2.8 m

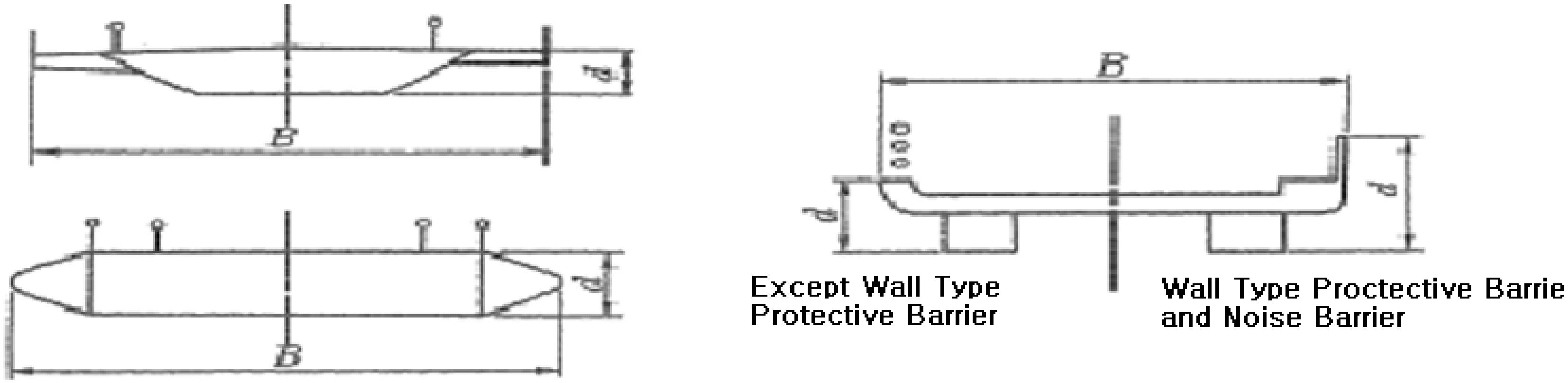
Simple Eigen Value Calculation

- **(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**

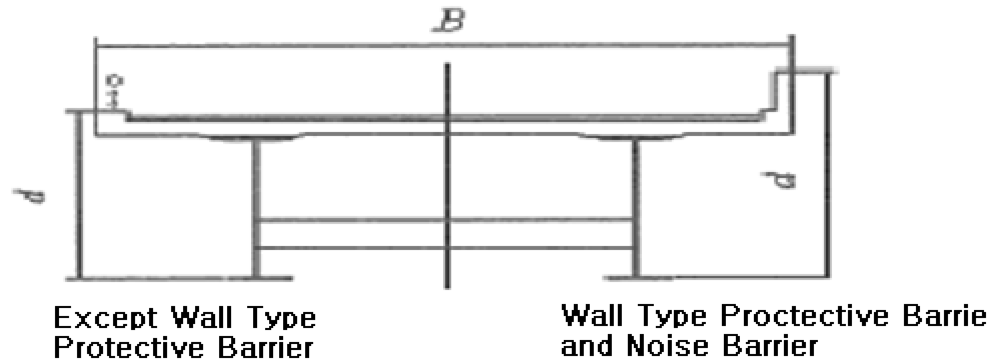
Flutter Velocity(U_{cf})

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

- B （Deck Width）＝ 33.18 m （USA Br.）



(b) Box Type Section



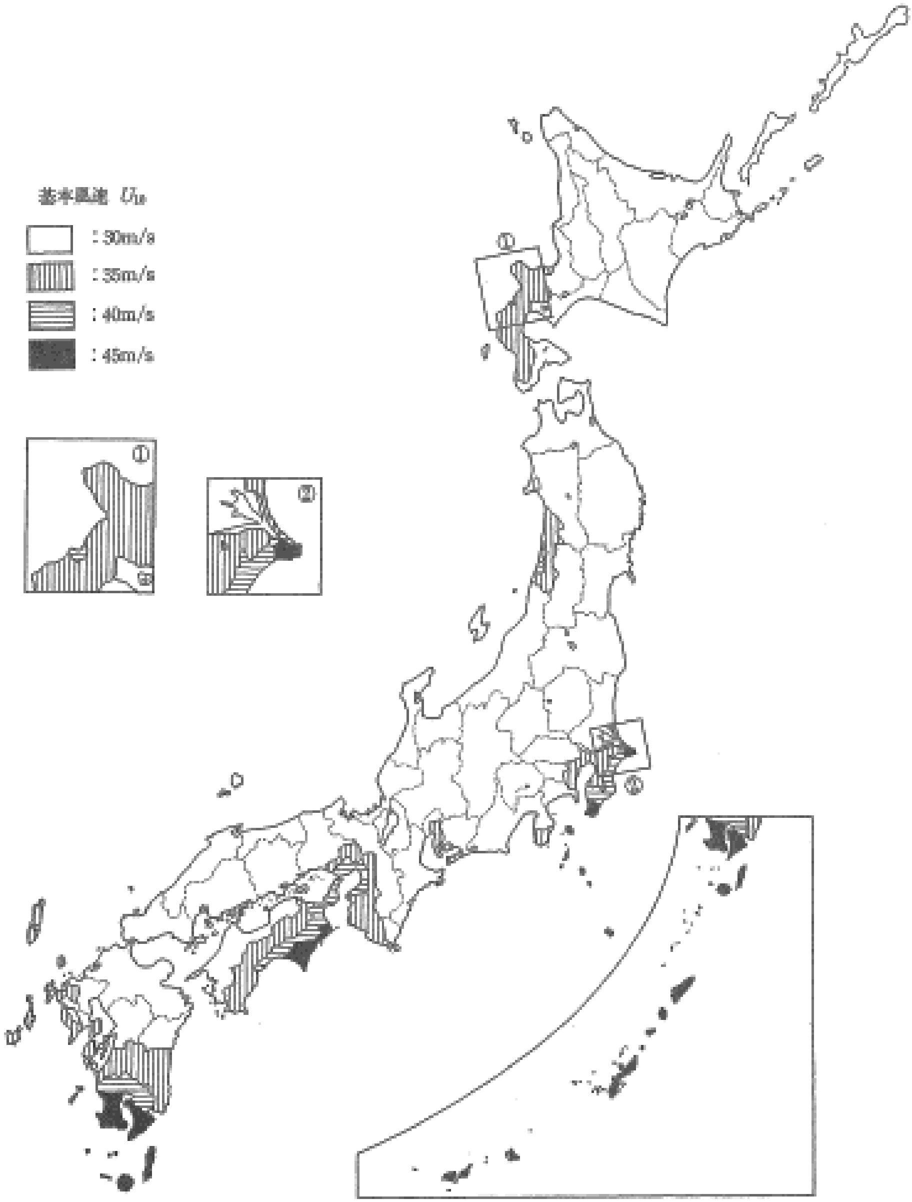
(c) I Type Section

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*

E1



図－4.1　基本風速 U_{10}

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표 2.1.14 지역별 기본풍속

구분	지역	지명	기본풍속(m/s)
I	내륙	서울, 대구, 대전, 춘천, 청주, 수원, 추풍령, 전주, 익산, 진주, 광주	30
II	서해안	서산, 인천	35
III	서남해안 남해안 동남해안	군산 여수, 충무, 부산 포항, 울산	40
IV	동해안 제주지역 특수지역	속초, 강릉 제주, 서귀포 목포	45
V		울릉도	50

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 $E_{r1} = 1.15$**
- $U_{rf} = 1.2 \times 1.15 \times 38.5 = 53$ m/s
- **Then**
- **Ucf = 68 m/s > U_{rf} = 53 m/s**
- **Flutter is no problem.**

Terrain　Ⅰ

（b）　地表粗度区分Ⅰ

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Terrain Ⅱ

（c） 地表粗度区分 Ⅱ

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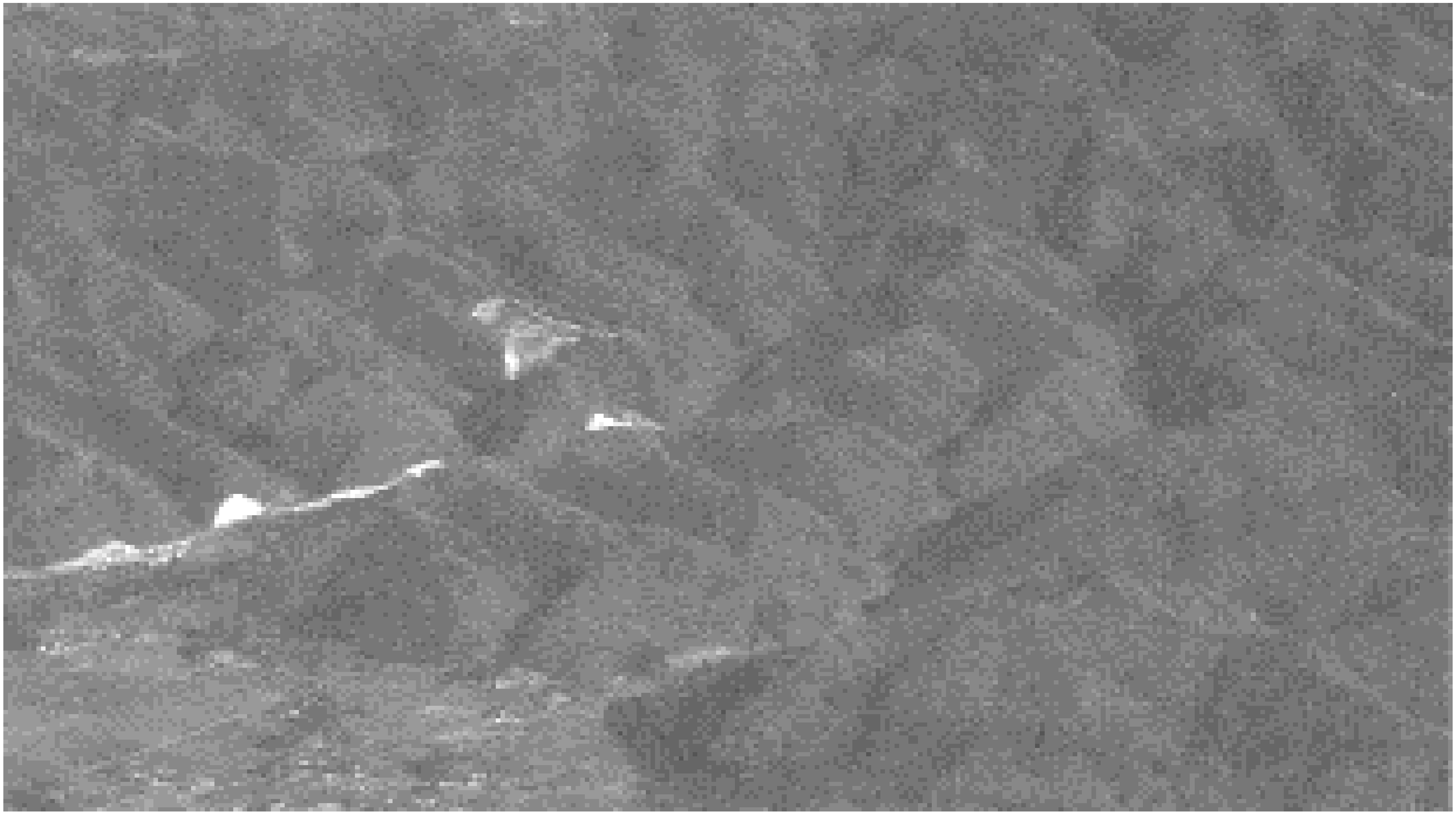
Terrain Ⅲ

（d） 地表粗度区分図

Terrain Ⅳ

(e)　地表粗度区分Ⅳ

Terrain Ⅴ



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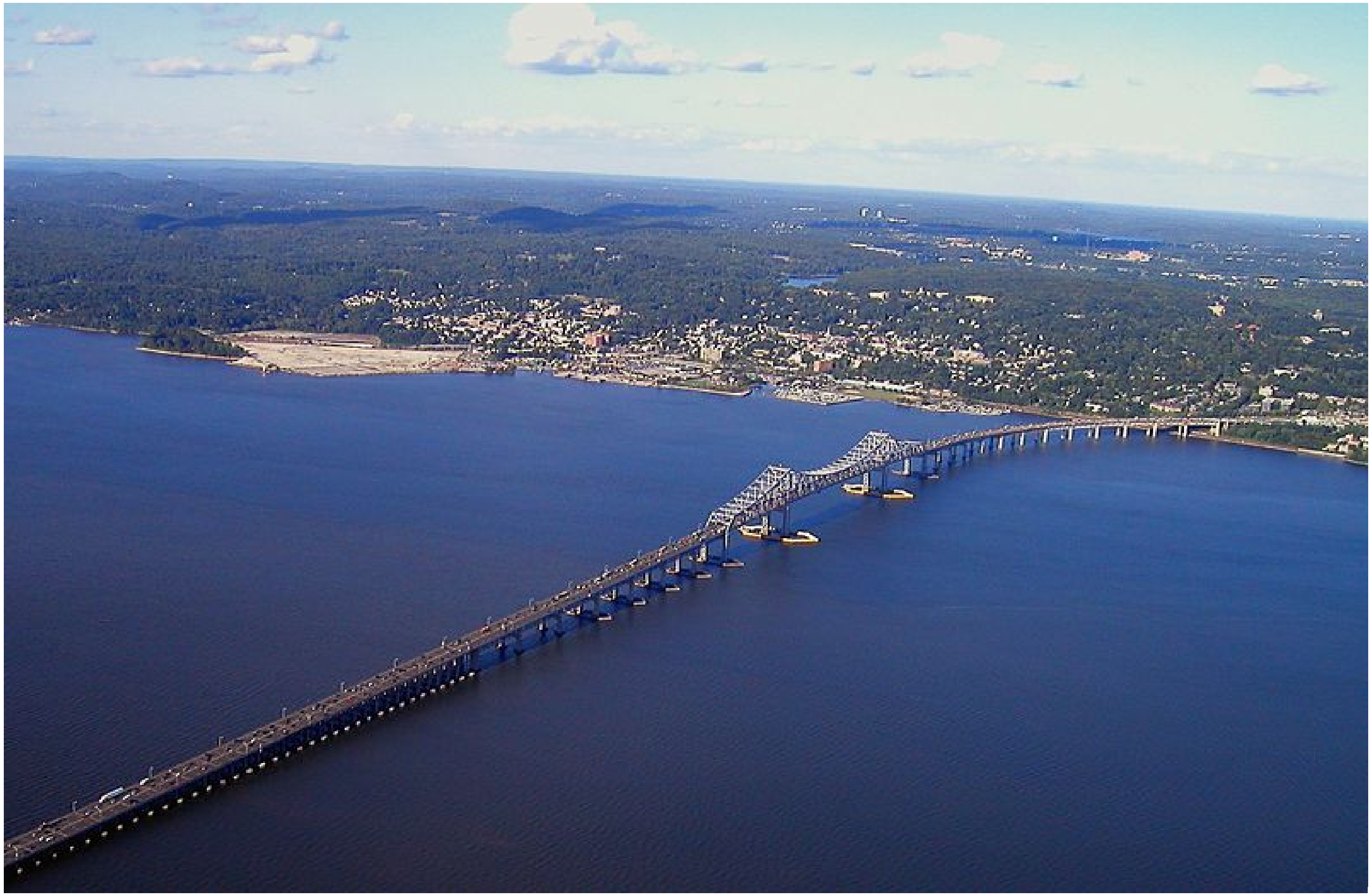
USA Bridge （Terrain Ⅱ）



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

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

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

- U_{rg} = 1.2 × U_d ……………… （5.12）
- = 1.2 × 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.

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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

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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）
- $\beta_h = 0.05 \ (B/d)^{-1} \cdot \beta_{ds}$ ……………….（5.24）
- $(B/d)^{-1} = (33.18/2.8)^{-1} = 0.084$
- β_{ds} = 1 （Section is almost hexagonal）
- Then、 $\beta_h = 0.05 \times 0.084 \times 1 = 0.0042$

Hexagonal Deck

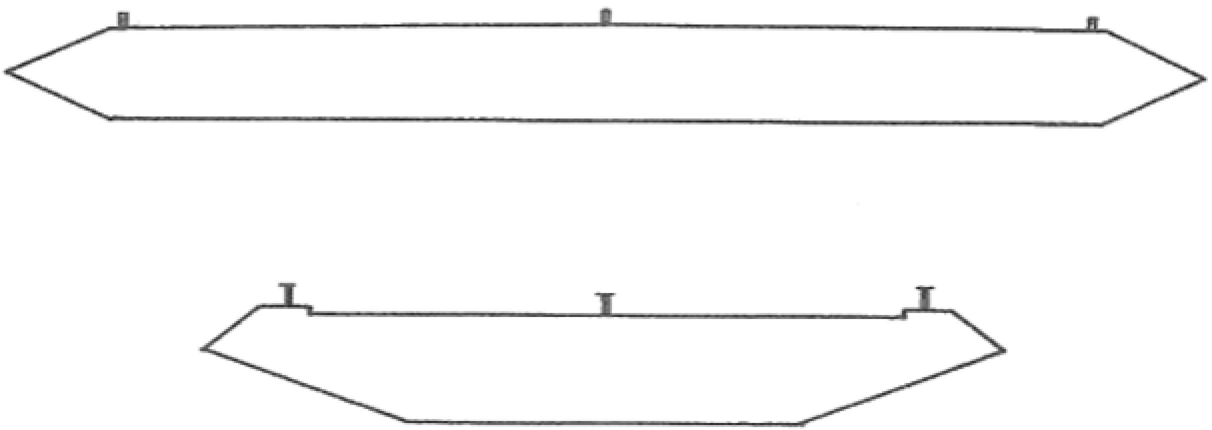
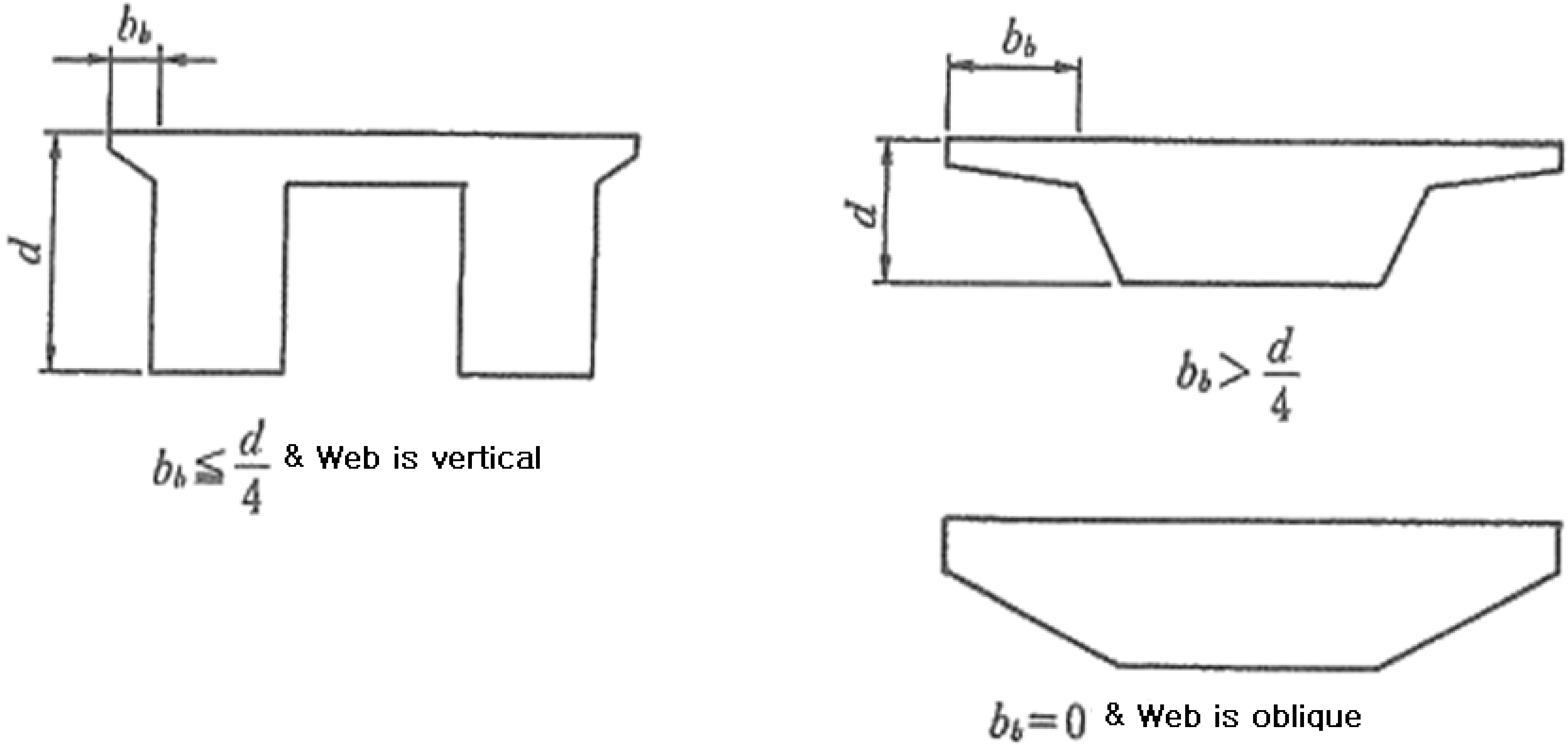


Fig.-5 Example of Hexagonal Deck



(a) $\beta_{ds} = 2$

(b) $\beta_{ds} = 1$

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.

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

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

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

<table>
<tr><th rowspan="2">B/d \ I_w</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></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>0</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（$=m/(\rho B^2)$）
- Box Girder Deck（Option 1）
- Concrete Deck （Option 2）

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- （ｉ）**Amplitude of Box 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**

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③ Conclusion

- We must be careful that there is possibility as follows;
- At wind velocity **18m/s**
- **Box 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.**

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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）
- $\vartheta_e = \beta_{\vartheta} / (I_{pr} \cdot \delta_{\vartheta})$ .... （5.33）

- E_{ms} = 1.3 （Conventional Value）
- β_{ϑ} ＝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
- β_{ϑ} ＝13.2 x 0.0006 x 1 = 0.008

$$E_{ms} = \frac{\int_D \Phi^2 dx}{\int_D |\Phi| \Phi^2 dx} \quad \cdots\cdots\cdots\cdots \quad (5,40)$$

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

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- β_{ds} = 1 （Section is almost hexagonal）
- Then
- β_{ϑ} ＝13.2 x 0.0006 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 ＝$(0.3B)^2 \cdot m$ ……………… （5.37）

(ⅰ)Amplitude of Box Girder（Option 1）

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

③ Conclusion

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

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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

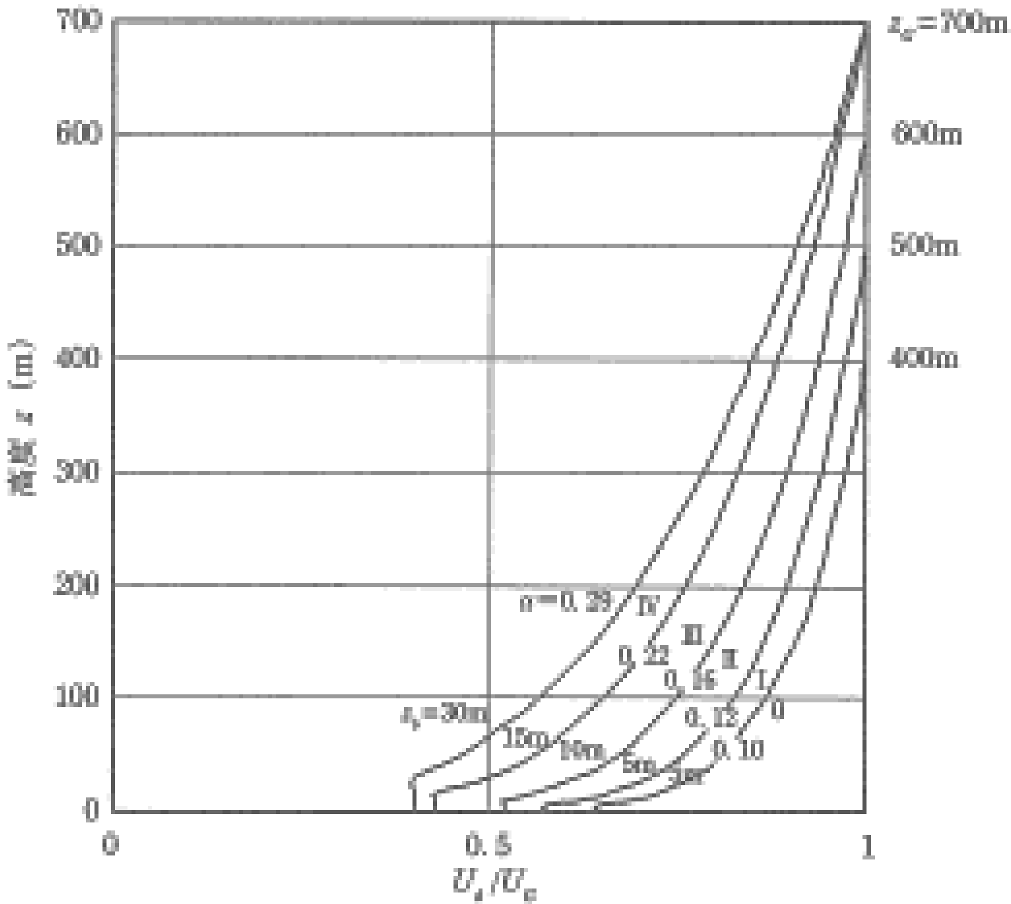
U_d: design basic velocity

U_G: Wind velocity where roughness of surface does not affect

z_b: Representative height of surface

α: Power Index

Model of Wind Profile



THANK YOU !!