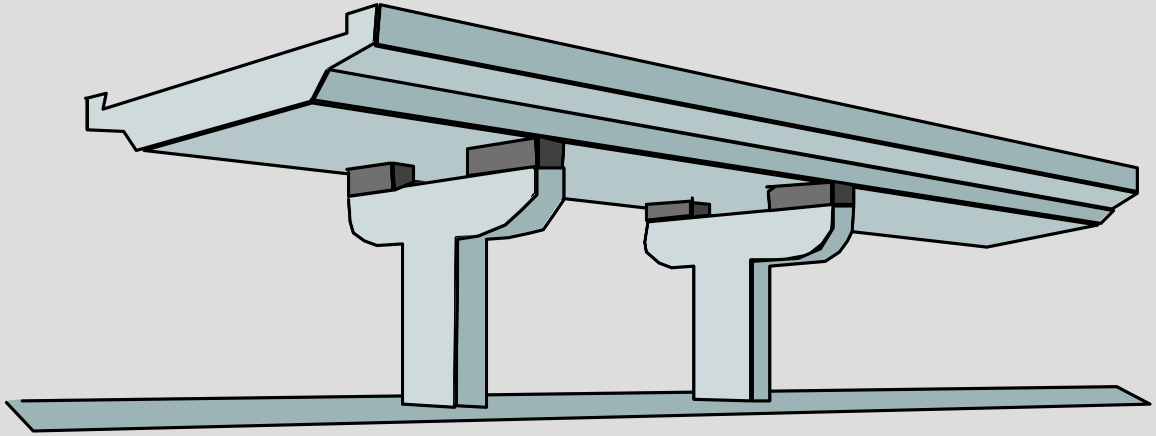
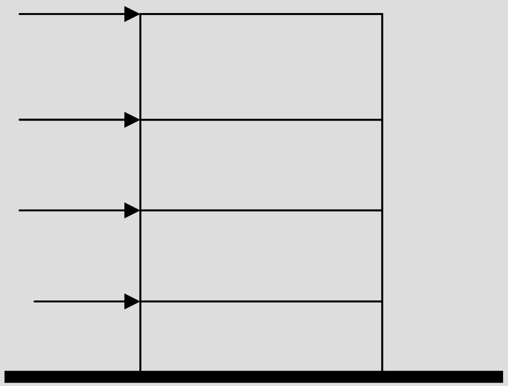
6. 橋梁の免震設計
6. Design of Isolated Bridges

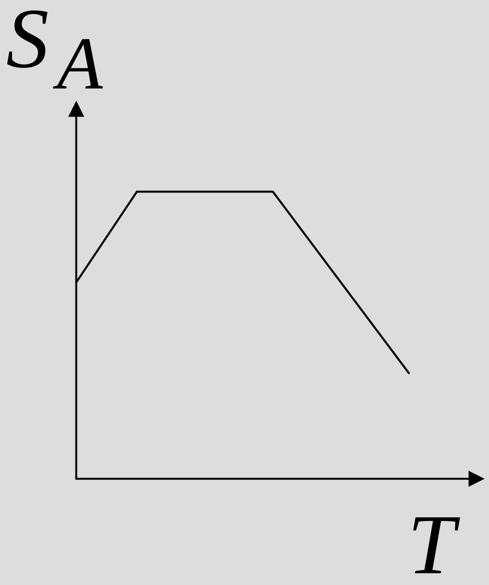


東京工業大学
川島一彦
Kazuhiko Kawashima
Tokyo Institute of Technology

Force Reduction Factor
荷重低減係数

Force Reduction Factor
荷重低減係数





$$F_{NL} = \frac{F_{EL}}{R}$$

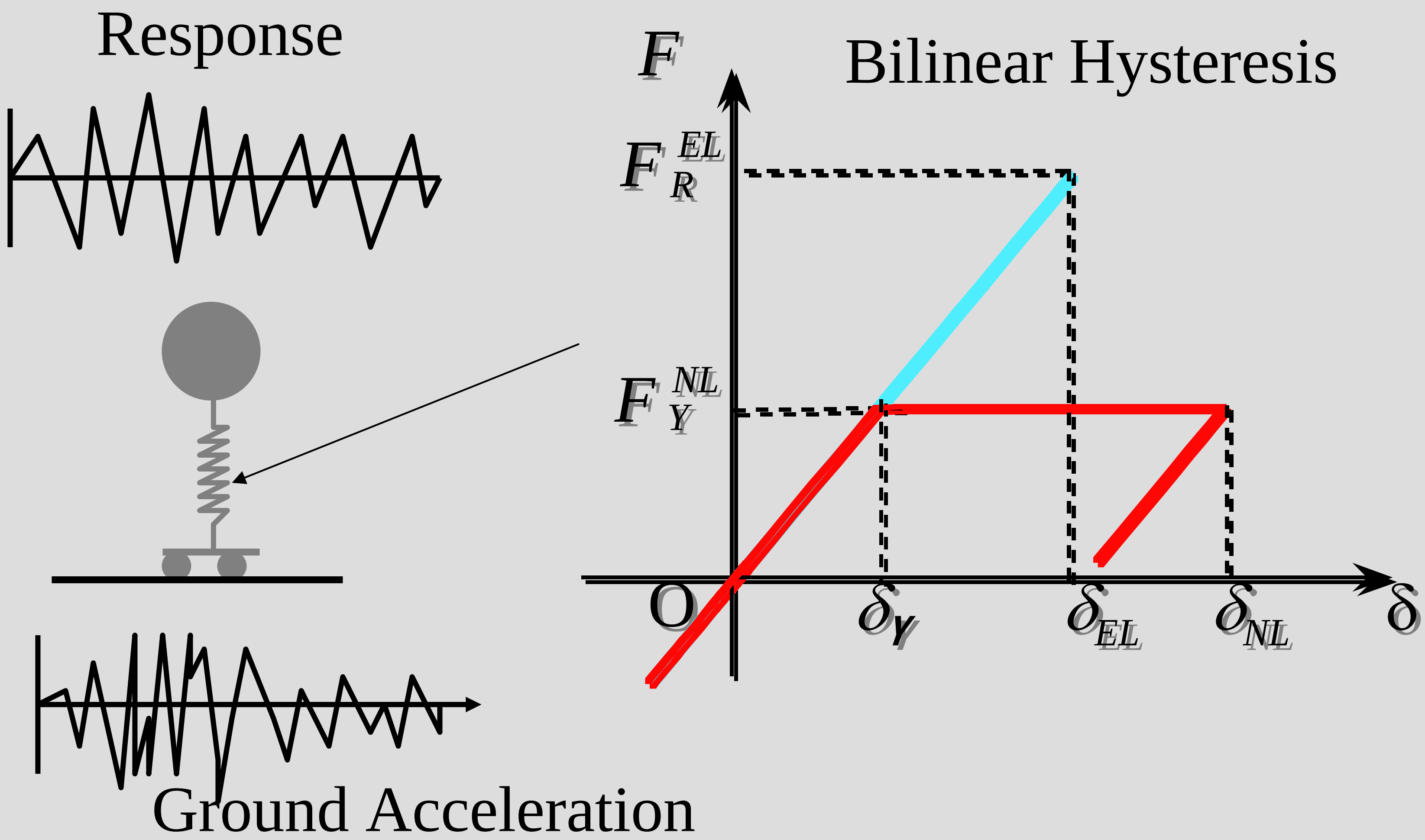
Elastic Inertia Force

$$F_{EL} = mS_A$$

Inertia Force considering nonlinear behavior of a structure

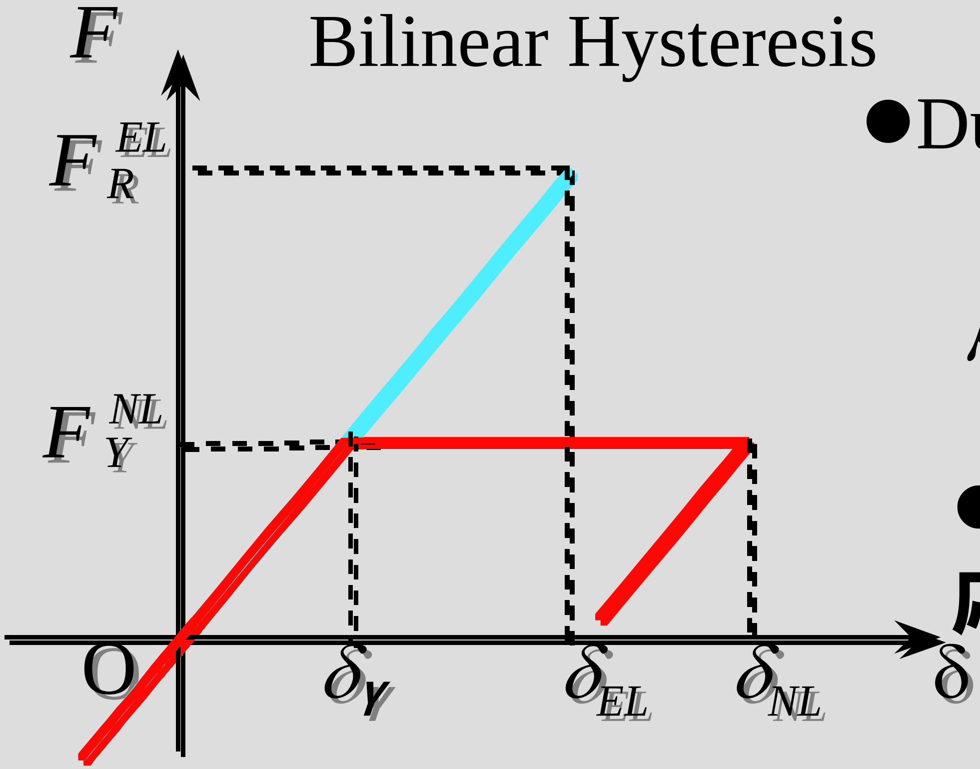
$$F_{NL} = ??$$

When a structure undergoes inelastic response under a strong ground motion, how does the structure response?



Ductility Factor じん性率

Bilinear Hysteresis



●Ductility capacityじん性率

$$\mu = \frac{\delta_u}{\delta_y}$$

●Response ductility factor
応答じん性率

$$\mu = \frac{\delta_{NL}}{\delta_y}$$

δ_y : yield displacement

δ_u : Ultimate displacement (capacity)

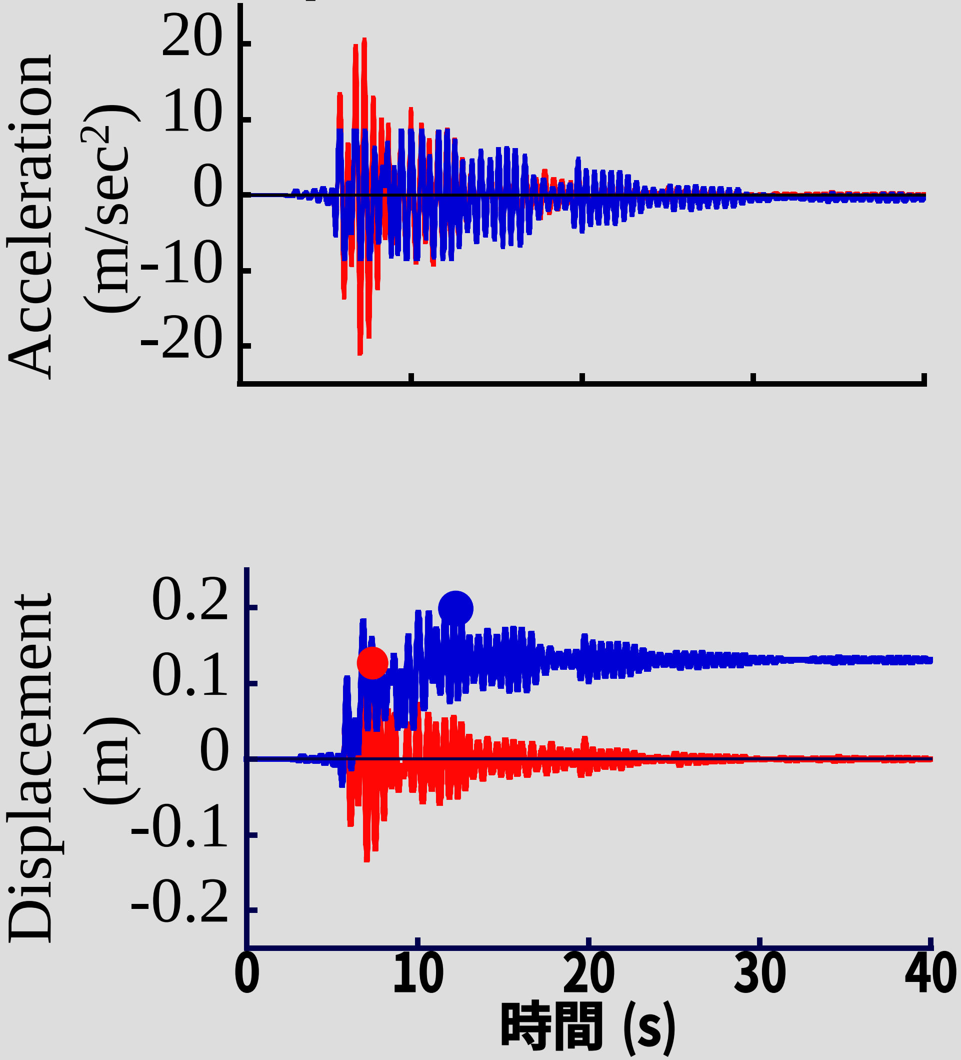
δ_{NL} : Maximum nonlinear response displacement

Target Ductility Factor 目標じん性率

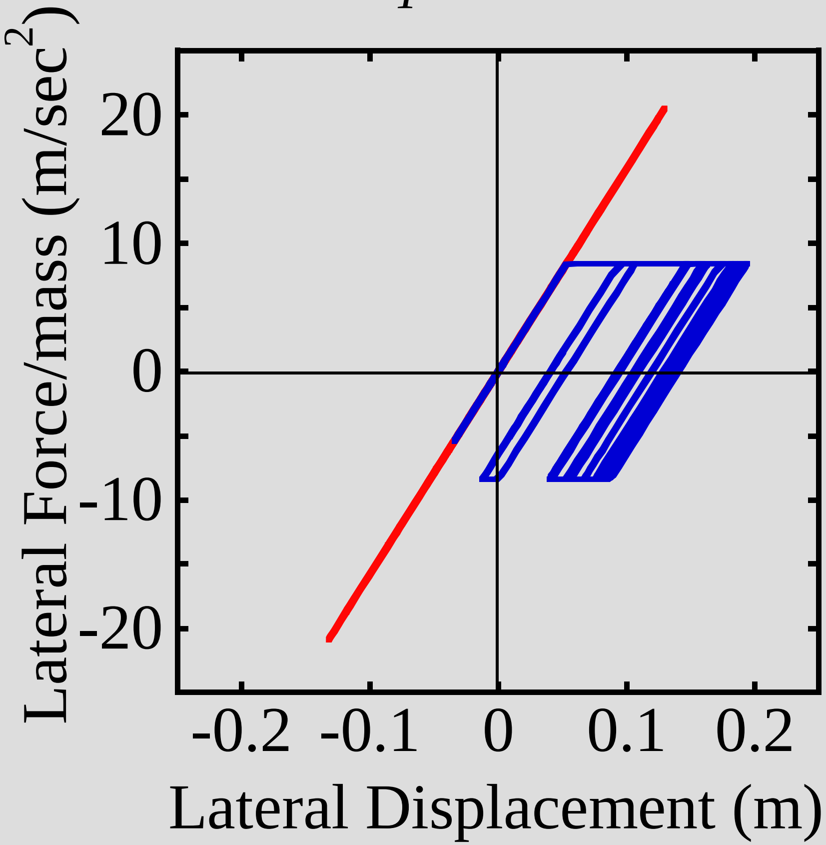
- Target ductility factor is a response ductility factor which is anticipated to occur in design
- If response ductility factor is less than the target ductility factor, designed structure must show expected performance
- If response ductility factor is larger than the target ductility factor, designed structure does not have expected performance.

Linear & Nonlinear Response of a SDOF Oscillator

Natural Period=0.5s, Target Ductility Factor = 4,
Yield Displacement = 53.3mm



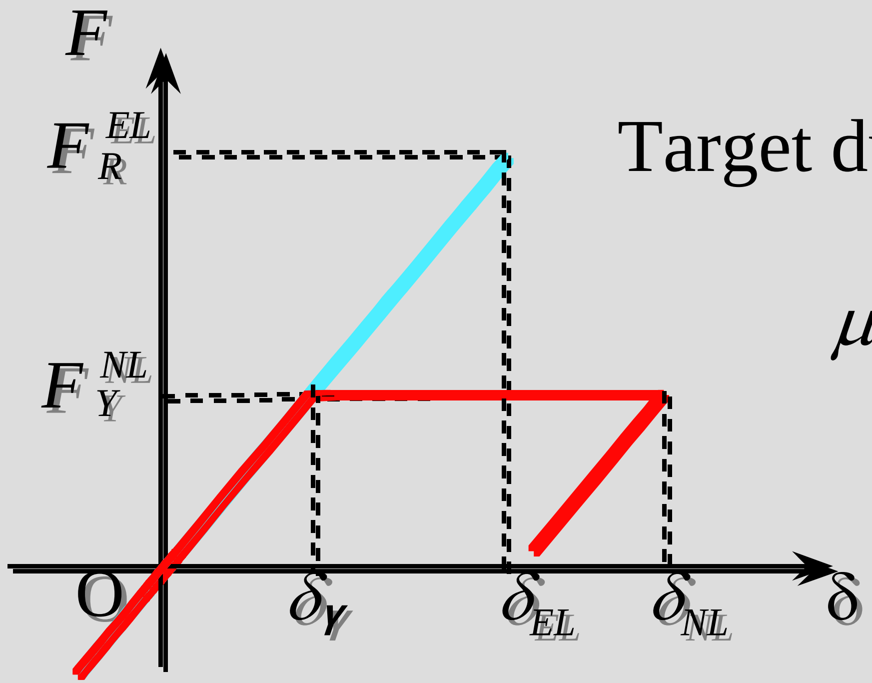
$$R_\mu = \frac{F_R^{EL}}{F_Y^{NL}} = 2.16$$



Force Reduction Factor　荷重低減係数

A basic parameter in the force-based seismic design

$$R_\mu(T,\mu_T,\xi_{EL},\xi_{NL}) = \frac{F_R{}^{EL}(T,\xi_{EL})}{F_R{}^{NL}(T,\mu_T,\xi_{NL})}$$



Target ductility factor

$$\mu_T = \frac{\delta_{NL}}{\delta_Y}$$

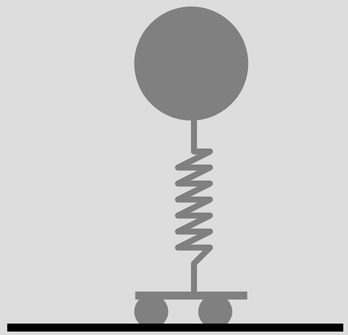
How is the Force Reduction Factor used in Seismic Design?

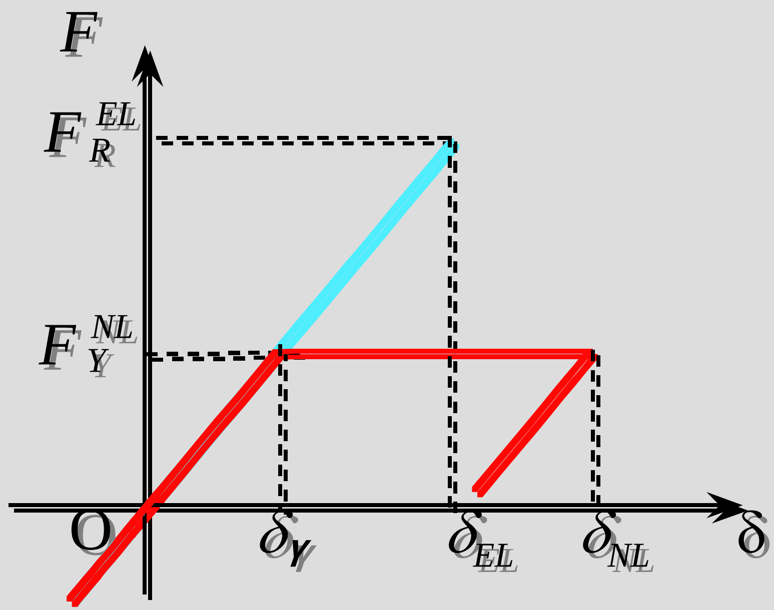
Elastic force can be approximately estimated as

$$F_R^{EL} \approx m \cdot S_A(T, \xi)$$

To design a structure so that the response ductility factor is less than the target ductility factor μ_T, the demanded capacity is evaluated as

$$F^{NL} = \frac{F_R^{EL}}{R_\mu}$$





Force Reduction Factor

A basic parameter in the Force-based Seismic Design

$$R_{\mu}(T,\mu_T,\xi_{EL},\xi_{NL})=\frac{{F_R}^{EL}(T,\xi_{EL})}{{F_R}^{NL}(T,\mu_T,\xi_{NL})}$$

- ✓ Force reduction factor
- ✓ Response modification factor
- ✓ q-factor
- ✓ R-factor
- ✓ ..

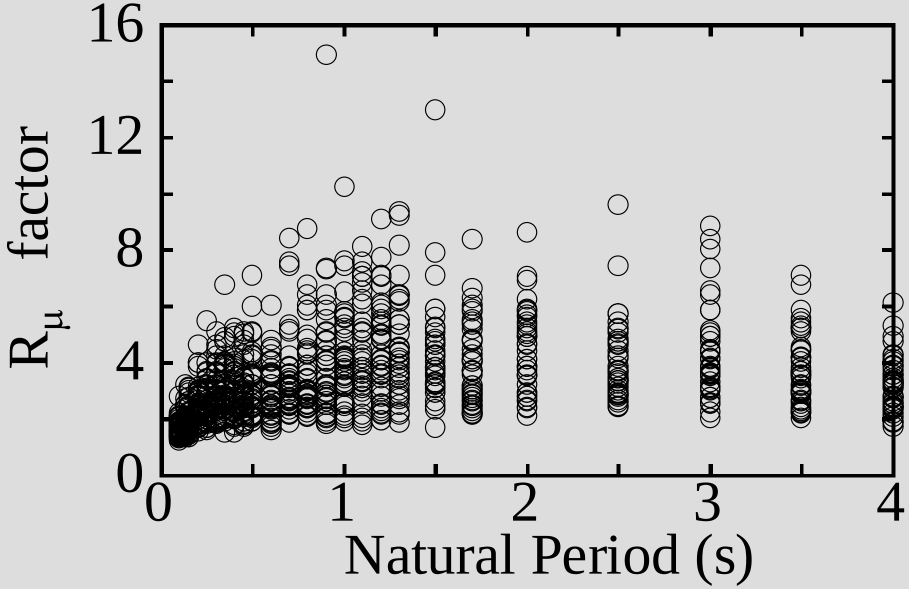
Force Reduction Factors for 70 Free-Field Ground Acceleration Records

Moderate Soils

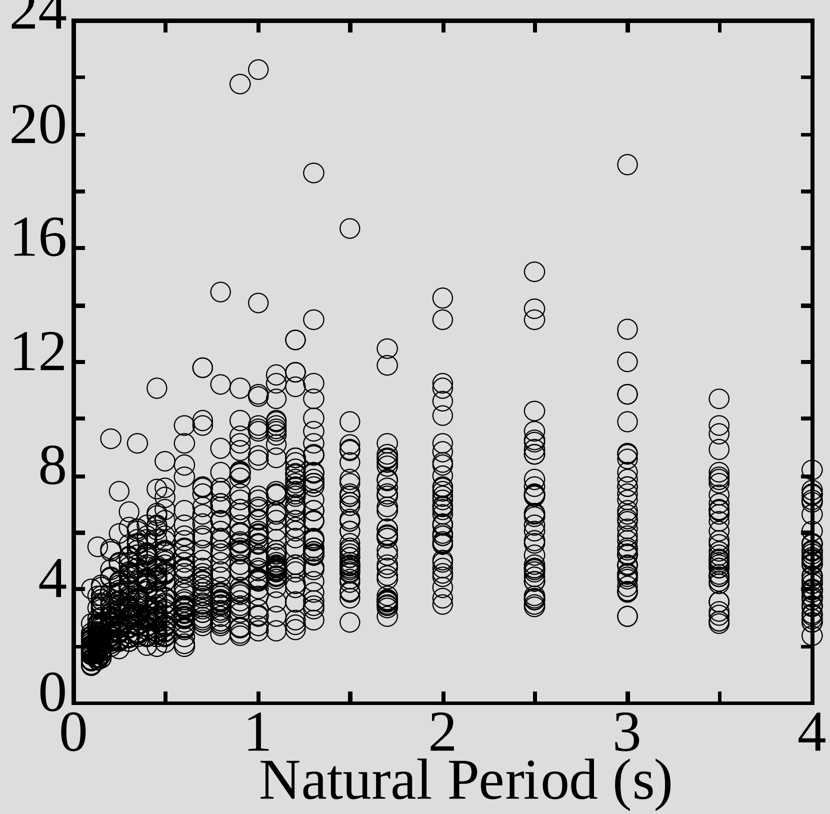
$\xi_{NL} = 0.02$

$\xi_{EL} = 0.05$

$\mu_T = 4$



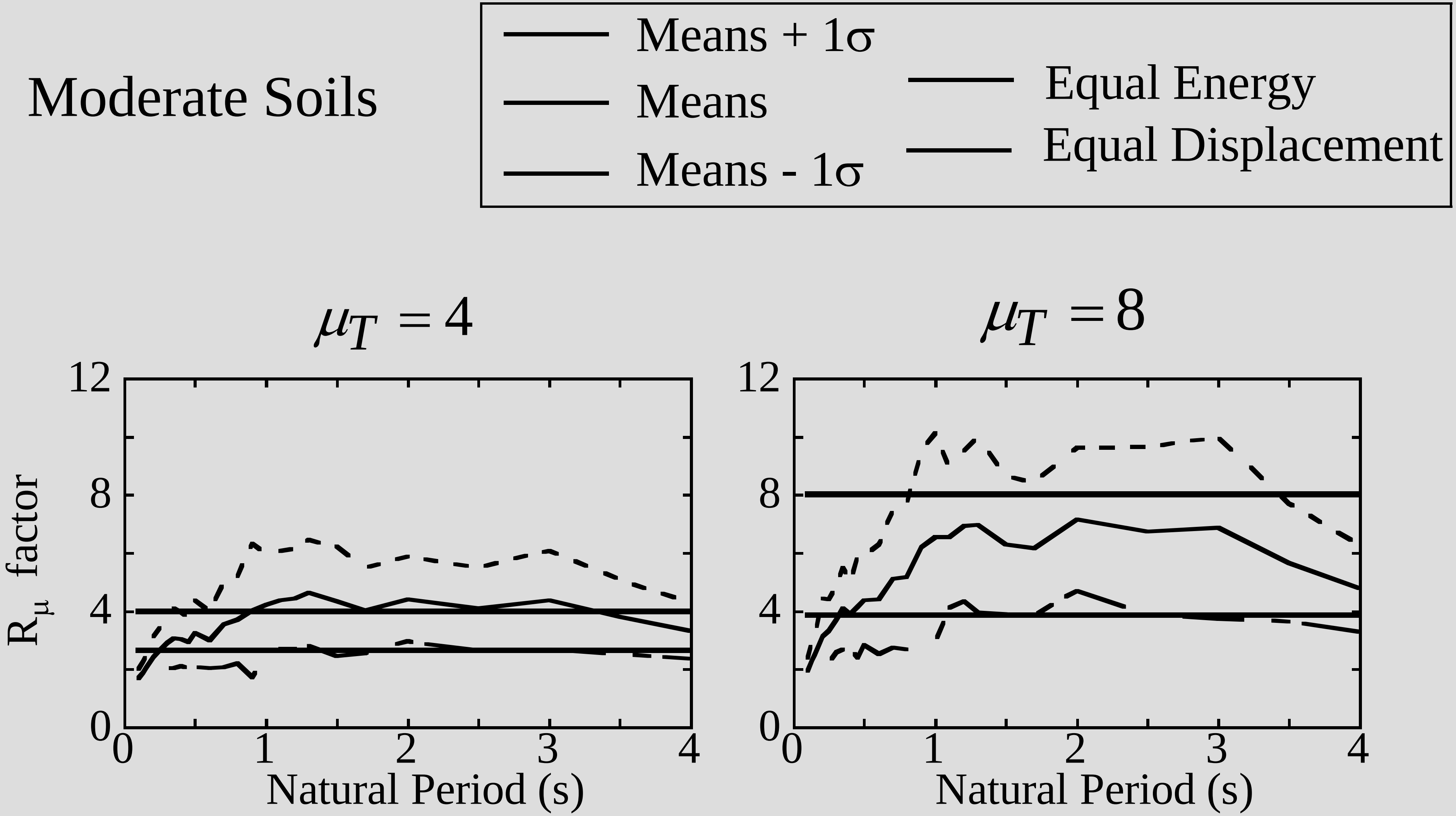
$\mu_T = 6$



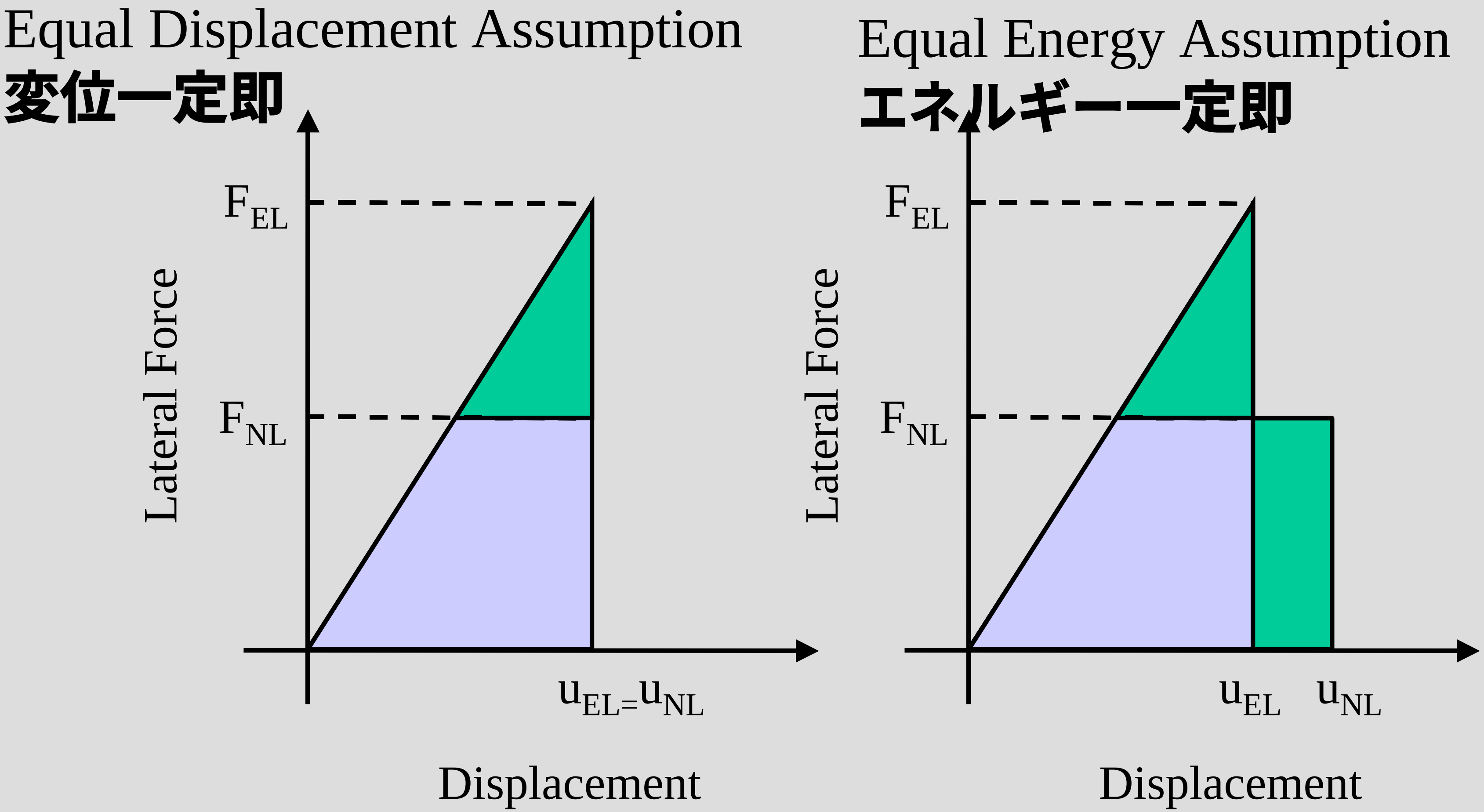
Watanabe & Kawashima (2002)

Evaluation of Force Reduction Factor Taking the Large Scattering into Account

Moderate Soils



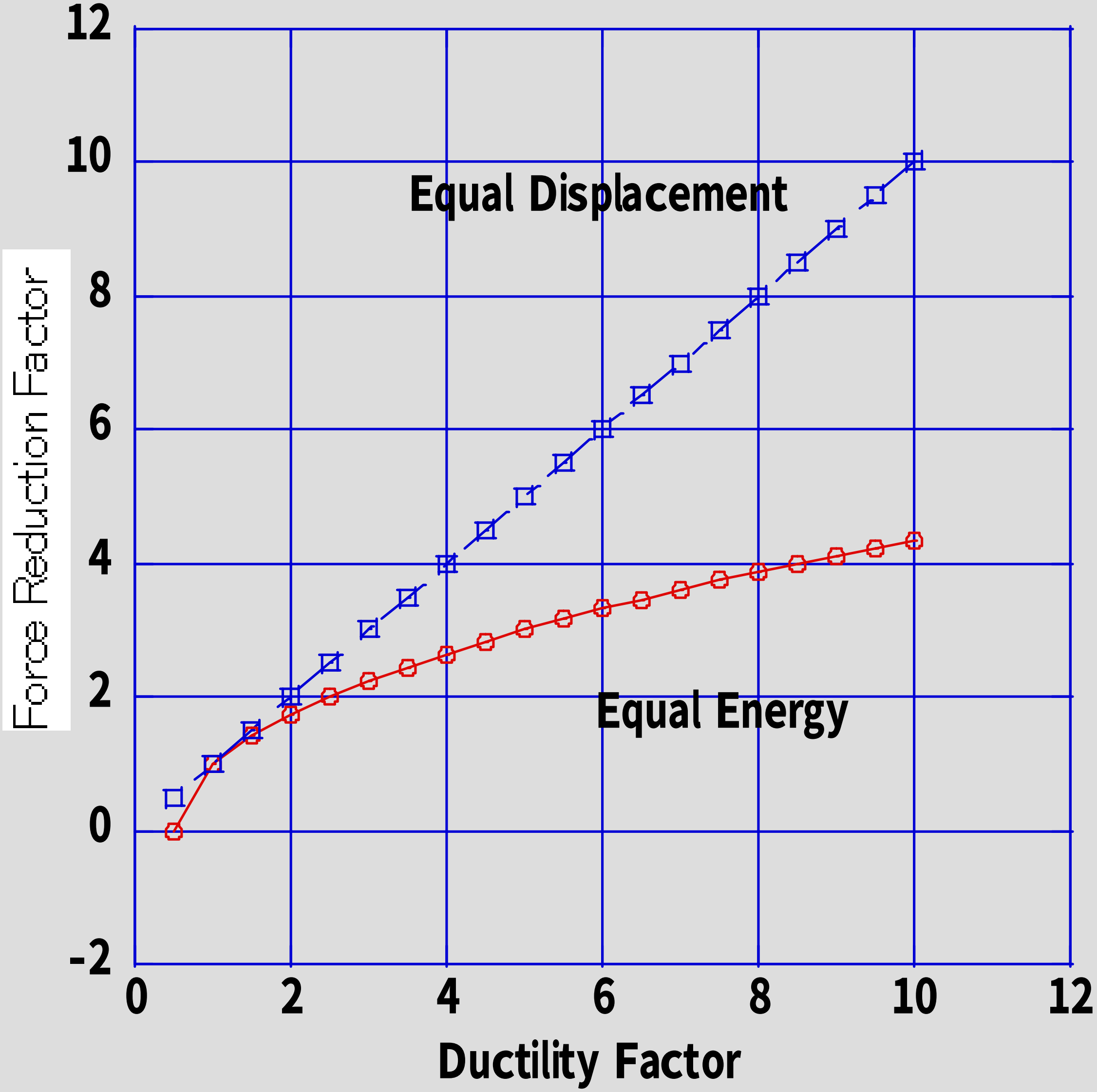
Approximate Estimates of the Force Reduction Factors 荷重低減係数の推定法



$$R_\mu = \mu$$

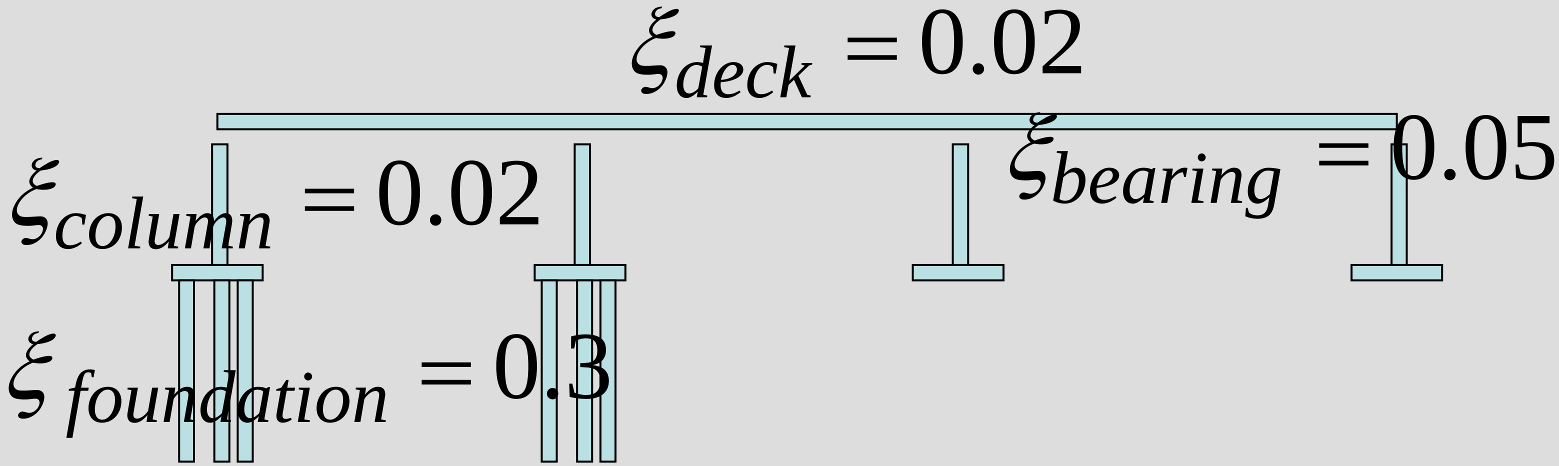
$$R_\mu = \sqrt{2\mu - 1}$$

Equal Energy vs. Equal Displacement



Evaluation of Modal Damping Ratio of a Bridge
橋梁系のモーダル減衰定数の推定

How can we determine the modal damping ratios by assigning damping ratios of each structural components?



●Theoretically, damping ratio can be defined only for a SDOF system. If we can assume the oscillation of each structural component as a SDOF system, it may be possible to assign a damping ratio for each structural component. This is called modal damping ratio.

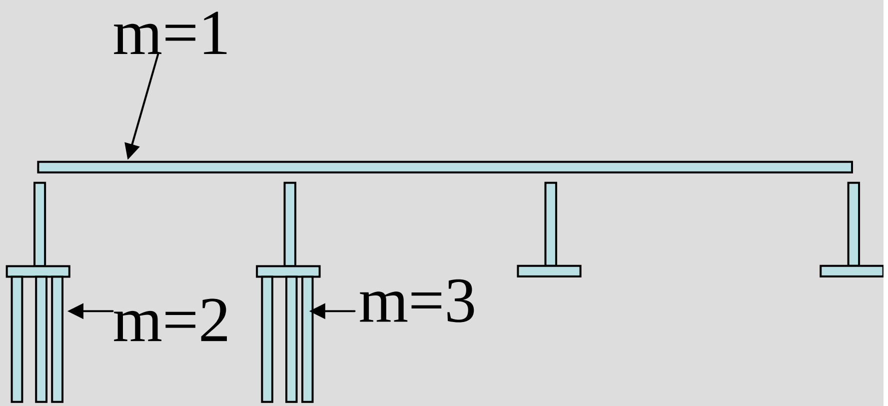
How can we determine the modal damping ratios by assigning damping ratios of each structural components? (continued)

- There is not a single method which is exact and easy for implementation for design purpose.
- Following empirical methods are widely used
  - ✓ Strain energy proportional method
  - ✓ Kinematic energy proportional method

Strain Energy Proportional Method
ひずみエネルギー比例減衰法

Method which averages damping ratio of each components with their strain energy as a weighting function

$$u_m(t) = \sum_{k=1}^{n} \phi_{km} q_m(t)$$



where

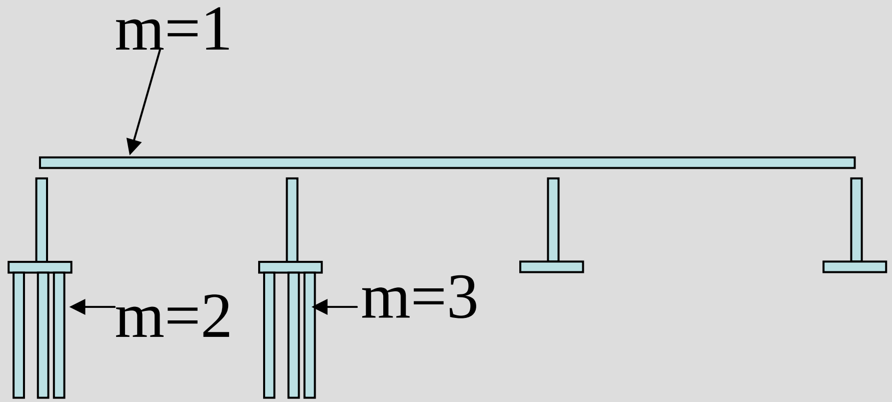
ϕ_{km} : mode shape of m-th element for k-th mode

k_m : stiffness matrix of m-th element

ξ_{km} : damping ratio of m-th element for k-th mode

Strain Energy Proportional Method

$$u_{km} = \phi_{km} \cdot q_{km}$$



$$f_{km} = k_m u_{km}$$

Strain energy of m-th element for k-th mode is

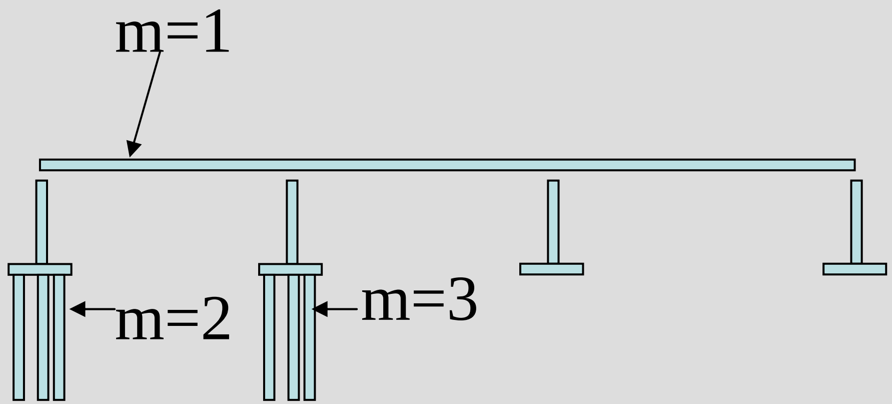
$$U_{km} = \frac{1}{2} f_{km}{}^T u_{km}$$

$$= \frac{q_{km}{}^2}{2} \phi_{km}{}^T k_m \phi_{km}$$

Therefore, the total energy dissipation of the system is

$$U_k = \sum_{m=1}^{n} \frac{q_{km}{}^2}{2} \phi_{km}{}^T k_m \phi_{km} \propto \sum_{m=1}^{n} \phi_{km}{}^T k_m \phi_{km}$$

$$\xi_k = \frac{\sum_{m=1}^{n} U_{km}\xi_{km}}{\sum_{m=1}^{n} U_{km}}$$



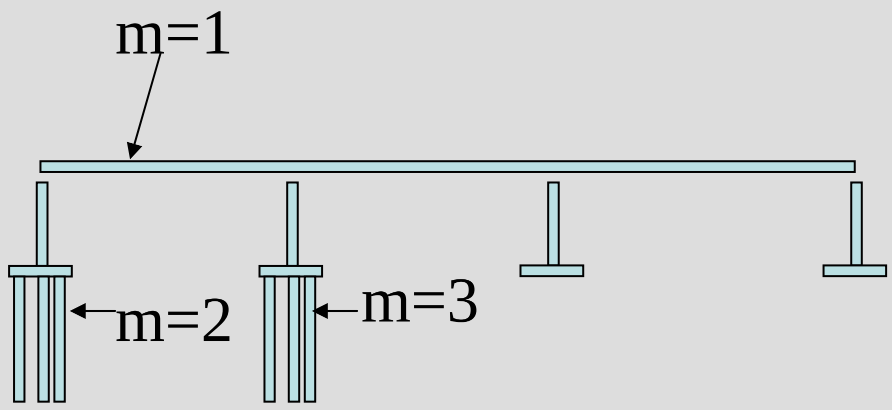
$$= \frac{\sum_{m=1}^{n} \xi_{km} \cdot \phi_{km}^{T} \cdot \mathbf{k}_m \cdot \phi_{km}}{\sum_{m=1}^{n} \phi_{km}^{T} \cdot \mathbf{k}_m \cdot \phi_{km}}$$

ξ_k is an averaged damping ration of a structure for k-th mode by taking the strain energy as a weighting function

Kinematic Energy Proportional Damping Ratio
運動エネルギー減衰法

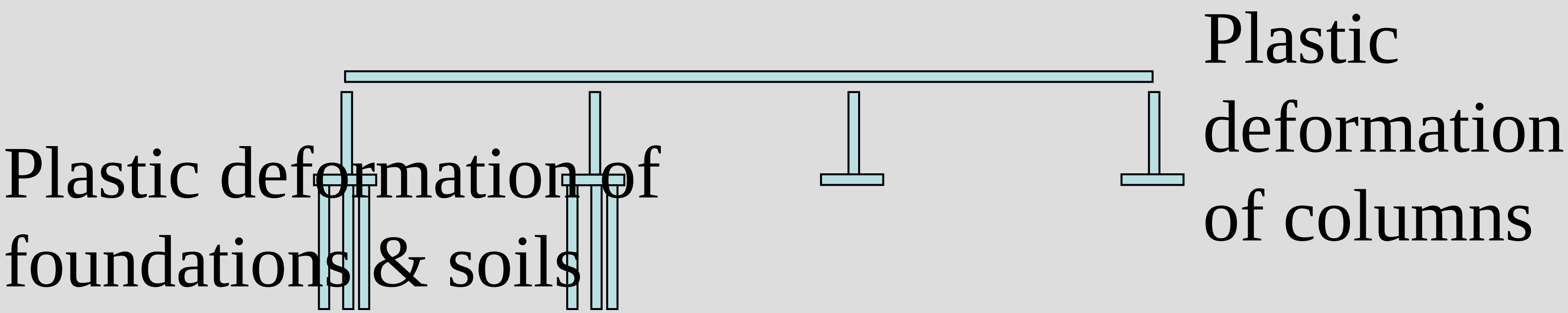
$$\xi_k = \frac{\sum_{m=1}^{n} \xi_{km} \cdot \boxed{\phi_{km}^T \cdot \mathbf{m}_m \cdot \phi_{km}}}{\sum_{m=1}^{n} \boxed{\phi_{km}^T \cdot \mathbf{m}_m \cdot \phi_{km}}} \qquad (2.7)$$

$$V_k \propto \sum_{m=1}^{n} \phi_{km}{}^T m_m \phi_{km}$$



Which is better for determining modal damping ratios between the strain energy proportional method and kinematic energy proportional method?

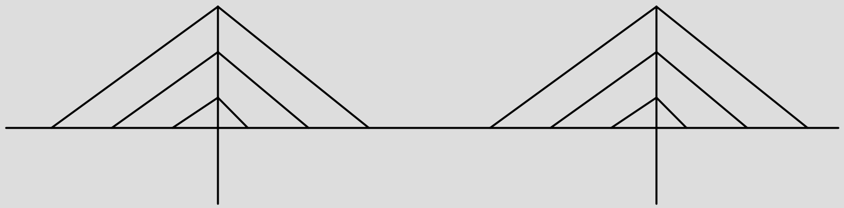
- Damping ratios of the structural components where large strain energy is developed are emphasized in the strain energy proportional method.



- Strain energy proportional method is better in a system in which hysteretic energy dissipation is predominant

Which is better for determining modal damping ratios between the strain energy proportional method and kinematic energy proportional method?

- Damping ratios of the structural components with larger kinematic energy are emphasized in the kinematic energy proportional method.



- Kinematic energy proportional method is better in a system in which hysteretic energy dissipation is less significant

Approximated Estimation of System Damping Ratio based on Energy Proportional Method

エネルギー比例減衰法に基づく橋梁の基本モーダル減衰定数の推定

構造全体系の減衰定数の評価

Evaluation of System Damping Ratio

Response modification factor resulting from enhanced energy dissipation capacity

First Mode Damping Ratio ξ	R. M. Factor R_E
$\xi < 0.1$	1.0
$0.1 \leq \xi < 0.12$	1.11
$0.12 \leq \xi < 0.15$	1.25
$0.15 \leq \xi$	1.43

Evaluation of first mode damping ratio based on energy proportion damping

Damping ratio for k-th structural component (ξ_k)

$$\xi = \frac{\sum \xi_k \cdot \phi_k{}^T \cdot k_k \cdot \phi_k}{\sum \phi_k{}^T \cdot k_k \cdot \phi_k}$$

Eq. (2.6)

構造全体系の減衰定数の評価

Evaluation of System Damping Ratio

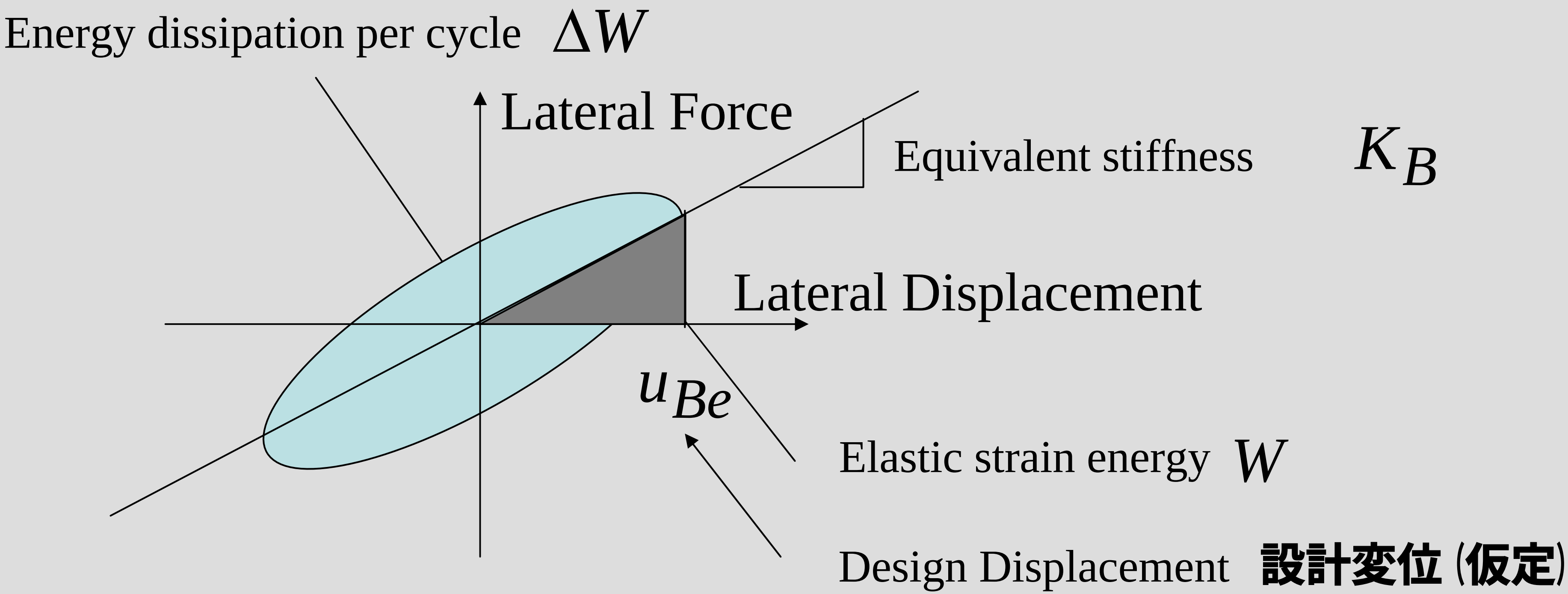
Evaluation of First Mode Damping Ratio based on Energy Proportion Damping

Damping Ratio for k-th Structural Component

$$\xi = \frac{\sum \xi_k \cdot \phi_k^T \cdot k_k \cdot \phi_k}{\sum \phi_k^T \cdot k_k \cdot \phi_k}$$

Structural Component	Damping Ratio ξ_k
Deck	0.03-0.05
Isolators	Equivalent damping ratio
Piers	0.05-0.1
Foundations	0.1-0.3

Evaluation of Energy Dissipation of Isolators and Dampers 免震装置の減衰定数の評価



Equivalent Stiffness
等価剛性

$$K_B = \frac{F(u_{Be}) - F(-u_{Be})}{2u_{Be}}$$

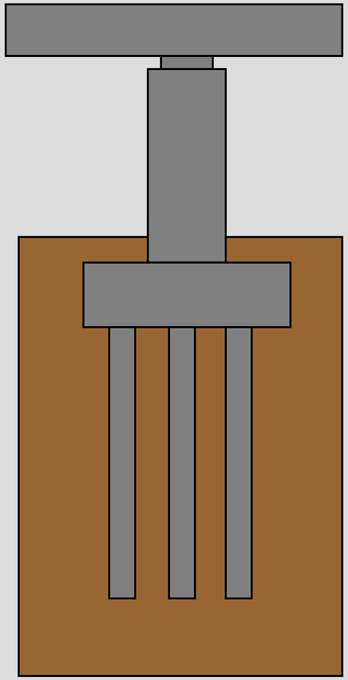
Equivalent Damping Ratio
等価減衰定数

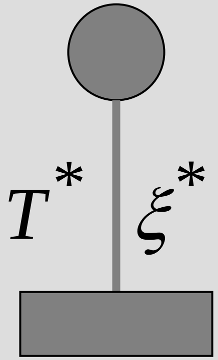
$$\xi_B = \frac{\Delta W}{4\pi W}$$

Static Inelastic Design for Seismic Isolated Bridges
免震設計の流れ

Evaluation of Demand for a Fixed Base Bridge

一般橋に対する非線形地震力の算出





$$D_{ave} = \frac{m \cdot S_A(T^*, \xi^*)}{R}$$

Response modification factor

荷重低減係数

$$R = \begin{cases} \sqrt{2\mu_r - 1} \\ \mu_r \\ \text{.........Empirical values} \end{cases}$$

How response ductility factor μ_r can be evaluated?

μ_r is not known at the first stage of the design, thus the response modification factor has to be pre-set as

$$R = \sqrt{2\mu_a - 1}$$

↑

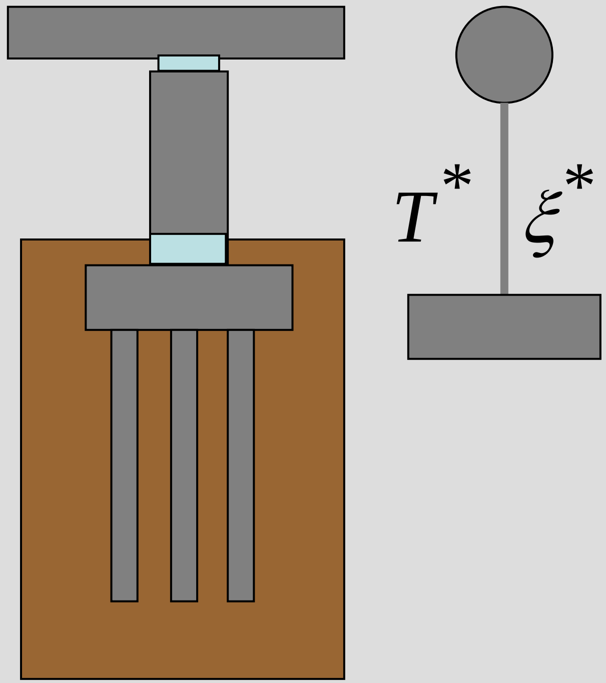
Design displacement ductility factor

設計じん性率

$$\because \quad \mu_r \approx (<) \mu_a$$

$$\gamma \cdot D_{ave} \leq \phi \cdot C_{ave}$$

Static Inelastic Analysis
免震橋の地震力の算出



Equivalent Lateral Force F_{eq}

$$F_{eq} = \frac{F}{R_I}$$

where

$$R_I = R_E \cdot R_\mu$$

R_μ = Response Modification Factor resulting from Inelastic Flexural Hysteresis of Piers**橋脚の曲げ塑性化に伴う荷重低減係数**

R_E = Response Modification Factor resulting from Enhanced Energy Dissipation Capacity**免震装置のエネルギー吸収性能の向上に基づく荷重低減係数**

Static Inelastic Analysis

$$R_I = R_E \cdot R_\mu$$

$$R_E = c_D(\xi_1)$$

$$= \frac{1.5}{40 \cdot \xi_1 + 1} + 0.5$$

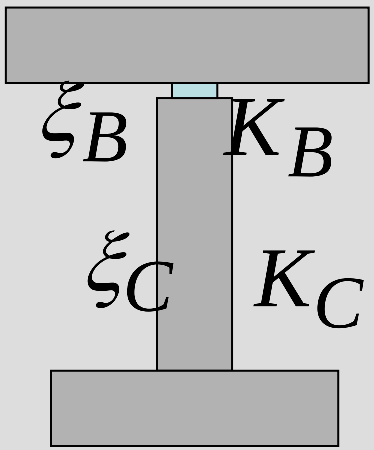
$$R_\mu = \begin{cases} \sqrt{2\mu_I - 1} \\ \mu_I \end{cases}$$

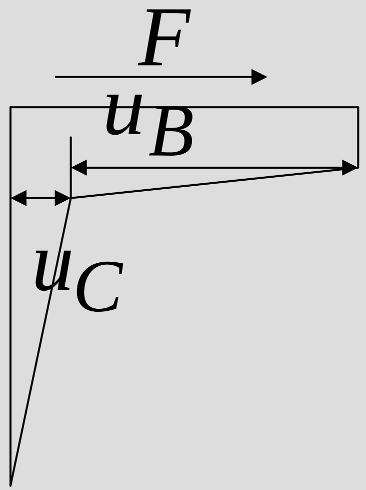
Since $\mu_{Ia} \approx (\geq) \mu_I$

$$R_\mu \approx \begin{cases} \sqrt{2\mu_{Ia} - 1} \\ \mu_{Ia} \end{cases}$$

Approximated Estimation of System Damping Ratio based on Energy Proportional Method
エネルギー比例減衰法に基づく免震設計の流れ

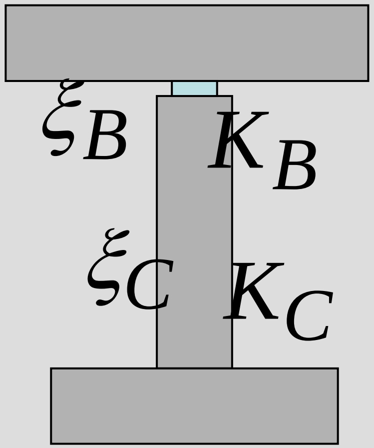
- Determine the system damping ratio of the fundamental mode based on damping ratio of a column and damping ratio of an isolator.
- Disregard the deformation and energy dissipation of the deck and foundation
- Fundamental mode shape can be approximated as

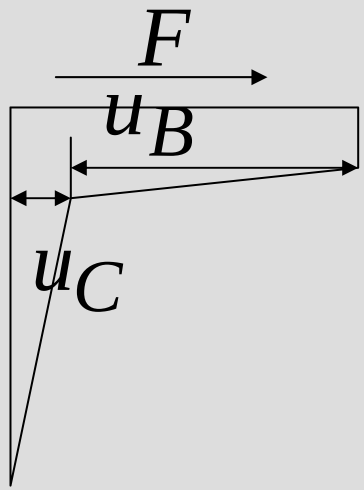




$$u_C = \frac{F}{K_C}$$

$$u_B = \frac{F}{K_B}$$





$$u_C = \frac{F}{K_C}$$

$$u_B = \frac{F}{K_B}$$

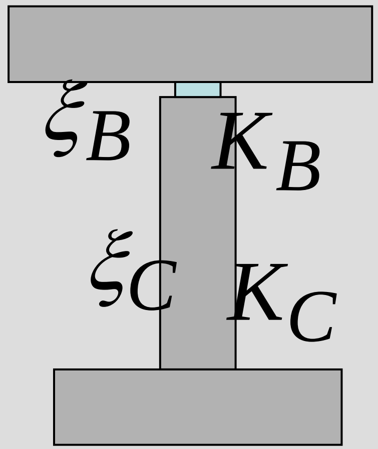
Strain energy of the column and the isolator

$$E_C = \frac{1}{2} K_C u_C^2 \quad = \frac{1}{2} K_C \left(\frac{K_B u_B}{K_C} \right)^2$$

$$= \frac{1}{2} \frac{K_B^2 u_B^2}{K_C}$$

$$E_B = \frac{1}{2} K_B u_B^2$$

Based on the strain energy proportional method, the system damping ratio for the 1st mode becomes as



$$E_C = \frac{1}{2}\frac{K_B{}^2 u_B{}^2}{K_C}$$

$$E_B = \frac{1}{2}K_B u_B{}^2$$

$$\xi = \frac{\xi_B E_B + \xi_C E_C}{E_B + E_C}$$

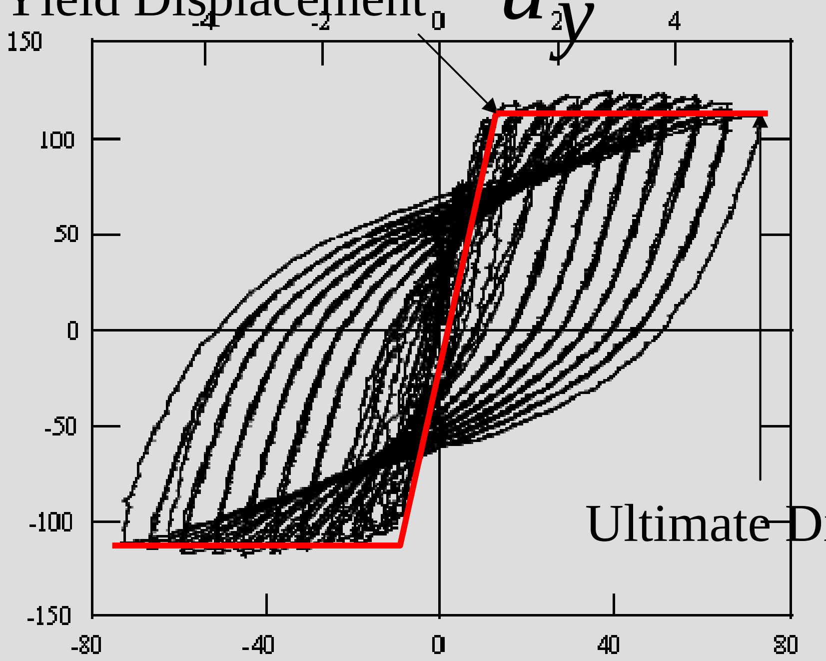
$$= \frac{\xi_B \dfrac{K_B u_B{}^2}{2} + \xi_C \dfrac{K_B{}^2 u_B{}^2}{2K_C}}{\dfrac{K_B u_B{}^2}{2} + \dfrac{K_B{}^2 u_B{}^2}{2K_C}} = \frac{\xi_B K_C + \xi_C K_B}{K_C + K_B}$$

Evaluation of Design Ductility Factor of RC Columns

設計じん性率 (許容じん性率)

Design response ductility factor of a pier

Yield Displacement u_y



Ultimate Displacement u_u

Fixed-base Bridge 非免震橋

$$\mu = 1 + \frac{u_u - u_y}{\alpha \cdot u_y}$$

Isolated Bridge 免震橋

$$\mu_m = 1 + \frac{u_u - u_y}{\alpha_m \cdot u_y}$$

$$\alpha_m = 2\alpha$$

Importance	Type-I GM	Type-II GM
Important Bridges	3.0	1.5
Less Important Bridges	2.4	1.2

Design of Isolators and Dampers
免震装置の設計

Design Requirements for Devices

●Computed displacement of the isolator should be within +/-10% from the assumed design displacement

●Shear strain of the isolator subjected to design lateral force should be less than 250%.

●Local shear strain resulting from the seismic effect, dead weight, rotation and other effects should be lass than rupture strain / 1.2.

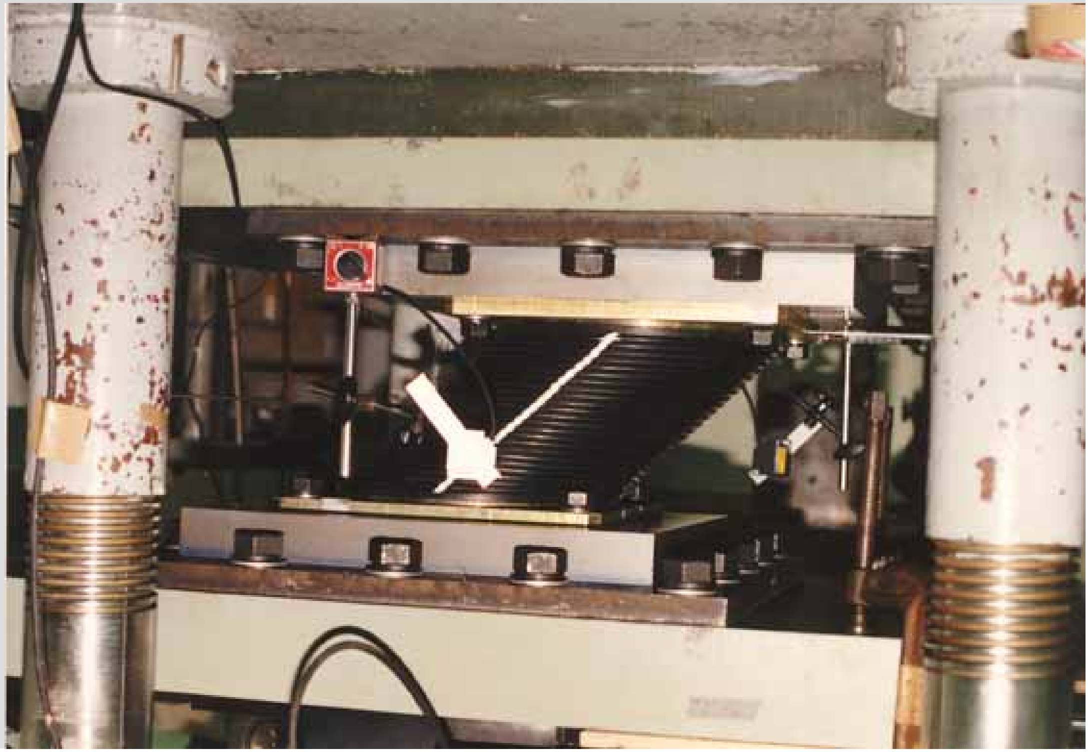
●Lateral capacity > Lateral force demand

Design of Isolators and Dampers

Design Requirements for Devices

- Devices having positive tangential stiffness at any displacement within the design displacement u_B should be used to prevent "shake down."
- Devices have to be designed & fabricated so that scatter of stiffness & equivalent damping ratio are within 10% of the design values
- Devices have to be stable for at least 50 & 15 lateral load reversals with the design displacement u_B for Type I & Type II ground motions, respectively.

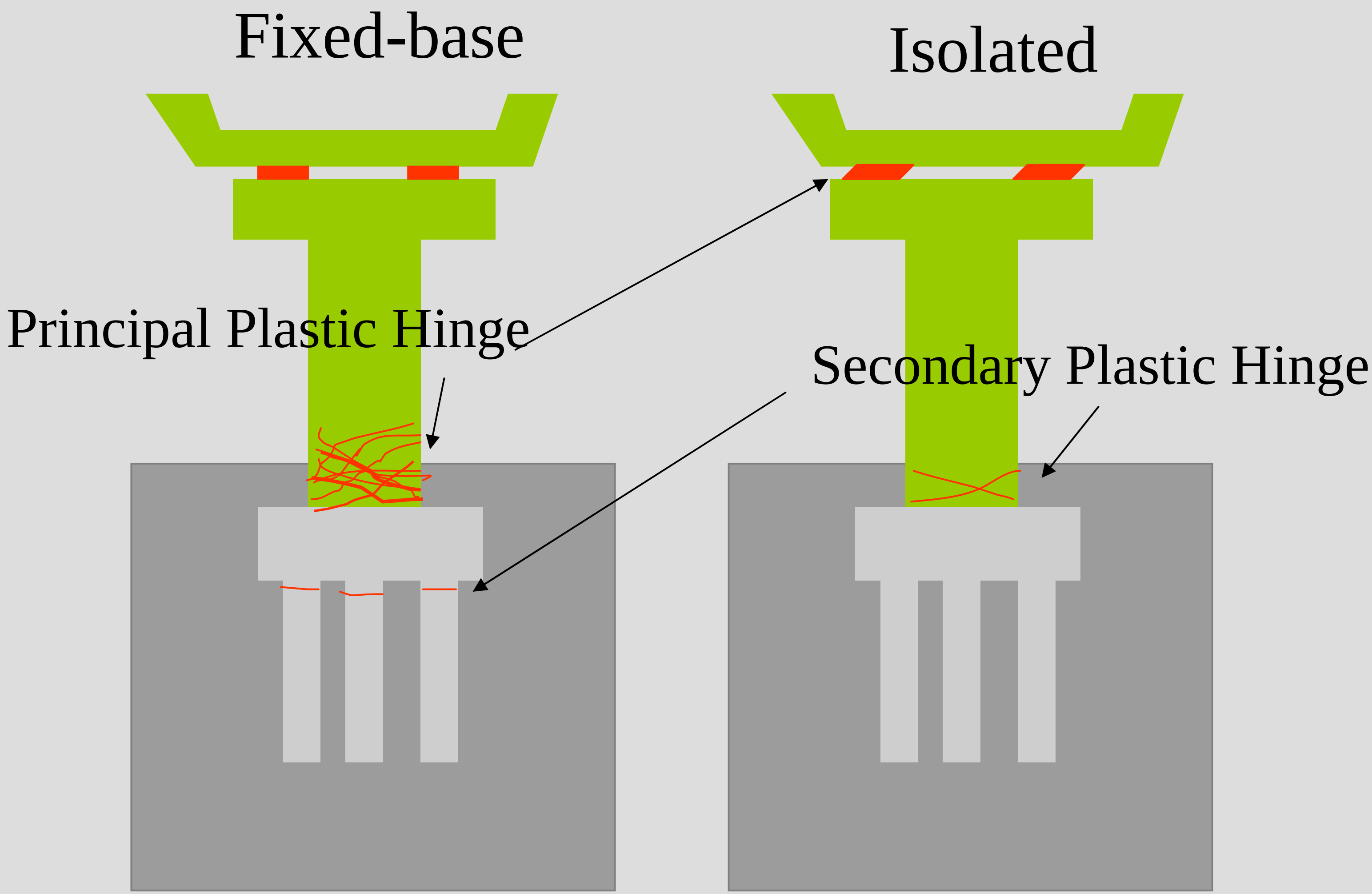
Deformation with
200% shear strain



Design Requirements for Devices (continued)

- A deck should return to the rest position after it is subjected to design ground motions. Residual displacement < 10% x design displacement.
- The stiffness and damping ratio should be stable for a change of load condition and natural environment

Damage Control of Columns in Isolated Bridges
構造系の損傷限界



ＬＲＢやＨＤＲを用いた免震設計の留意点
橋脚の塑性変形の影響

Effect of Column Deformation

Effect of Isolator Deformation on the System Ductility Factor構造系じん性率と橋脚系じん性率の関係

$$\mu_P = \frac{u_P^{\max}}{u_P^{P_y}} = \frac{u_P^{P_y} + u_{Pp}}{u_P^{P_y}} = 1 + \frac{u_{Pp}}{u_P^{P_y}}$$

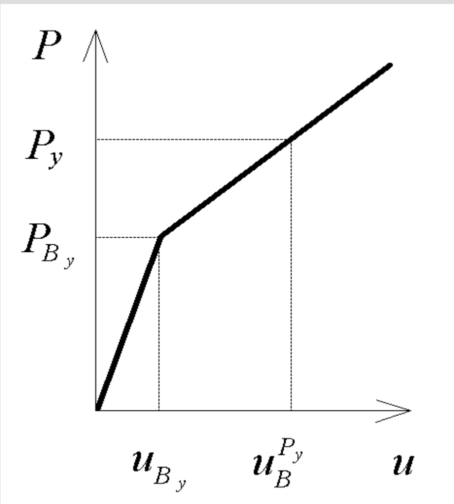
$\therefore$

$$u_{Pp} = u_P^{P_y}(\mu_P - 1)$$

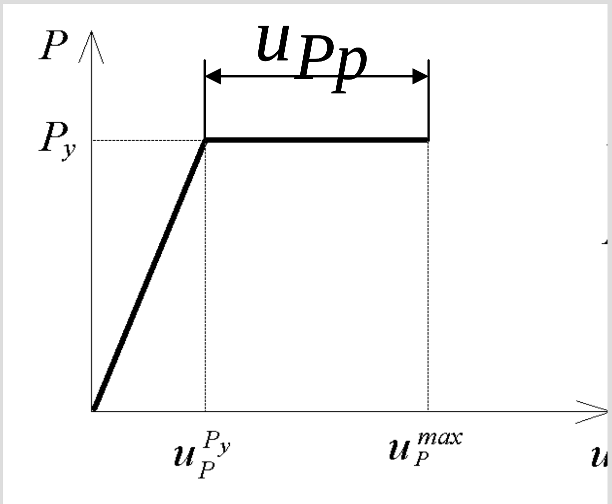
$$u^{\max} = u^{P_y} + u_{Pp}$$

$$u^{P_y} = u_P^{P_y} + u_B^{P_y}$$

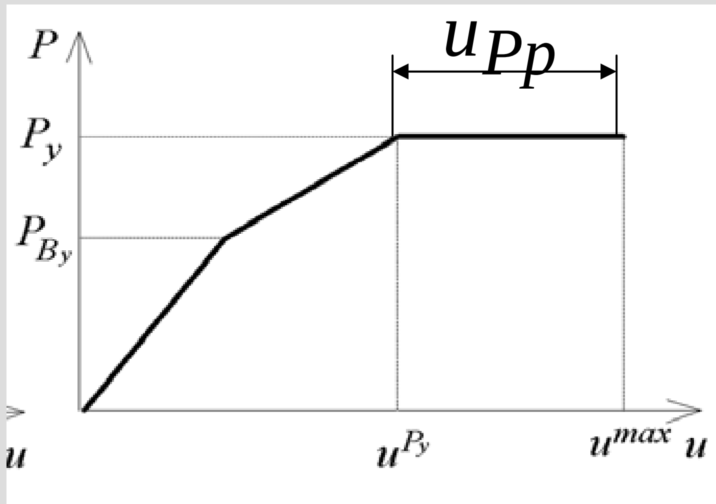
Isolators



Column



System



Effect of Isolator Deformation on the System Ductility Factor

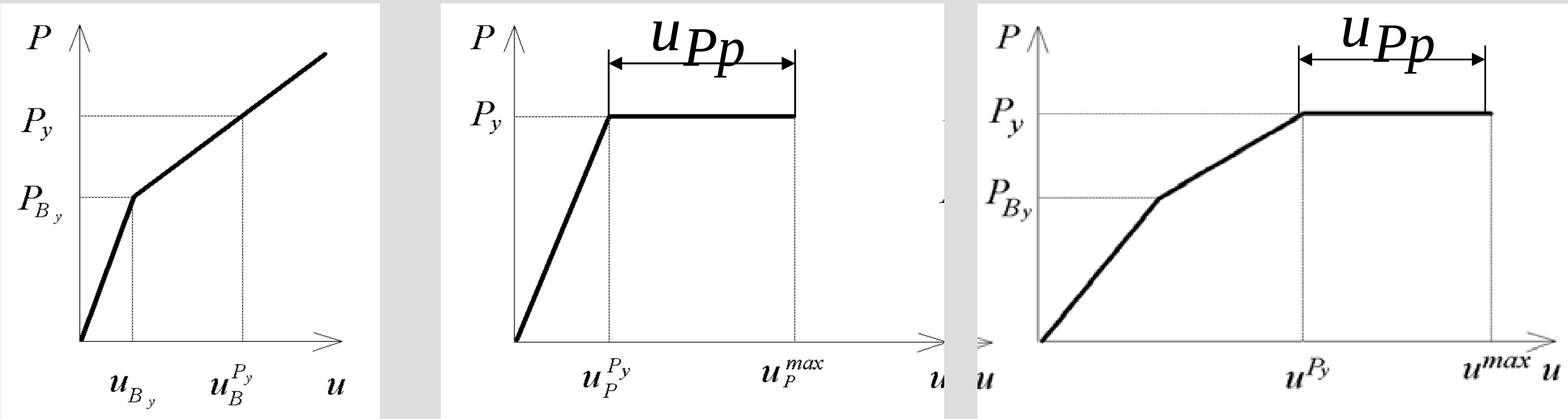
$$u^{\max} = u^{P_y} + u_{Pp}$$

$$u^{P_y} = u_P^{P_y} + u_B^{P_y}$$

$$\therefore \quad \mu_S = \frac{u^{\max}}{u^{P_y}} = 1 + \frac{\mu_P - 1}{1 + c_f}$$

$$c_f = \frac{u_B^{P_y}}{u_P^{P_y}}$$

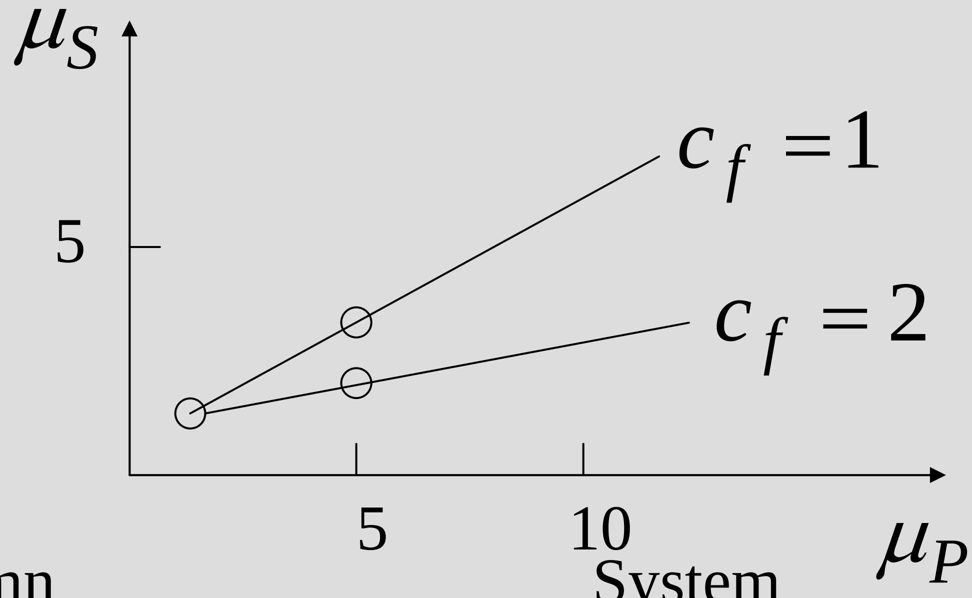
Isolators Column System



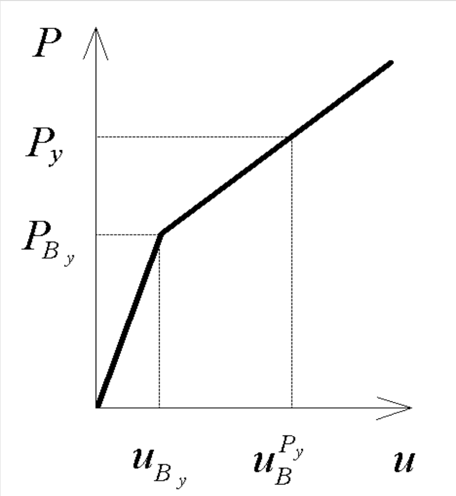
System Ductility Factor vs. Column Ductility

$$\mu_S = 1 + \frac{\mu_P - 1}{1 + c_f}$$

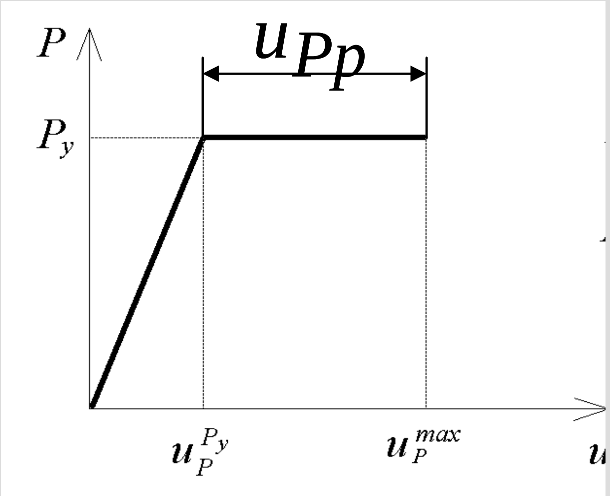
$$c_f = \frac{\dfrac{P_y}{u_B}}{\dfrac{P_y}{u_P}}$$



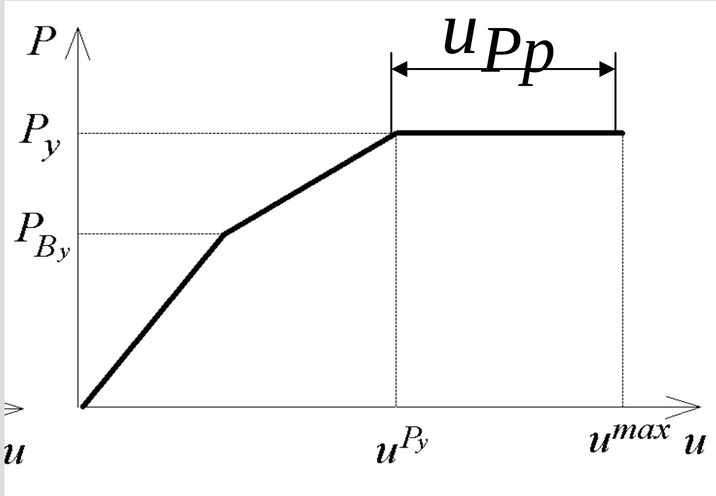
Isolators



Column

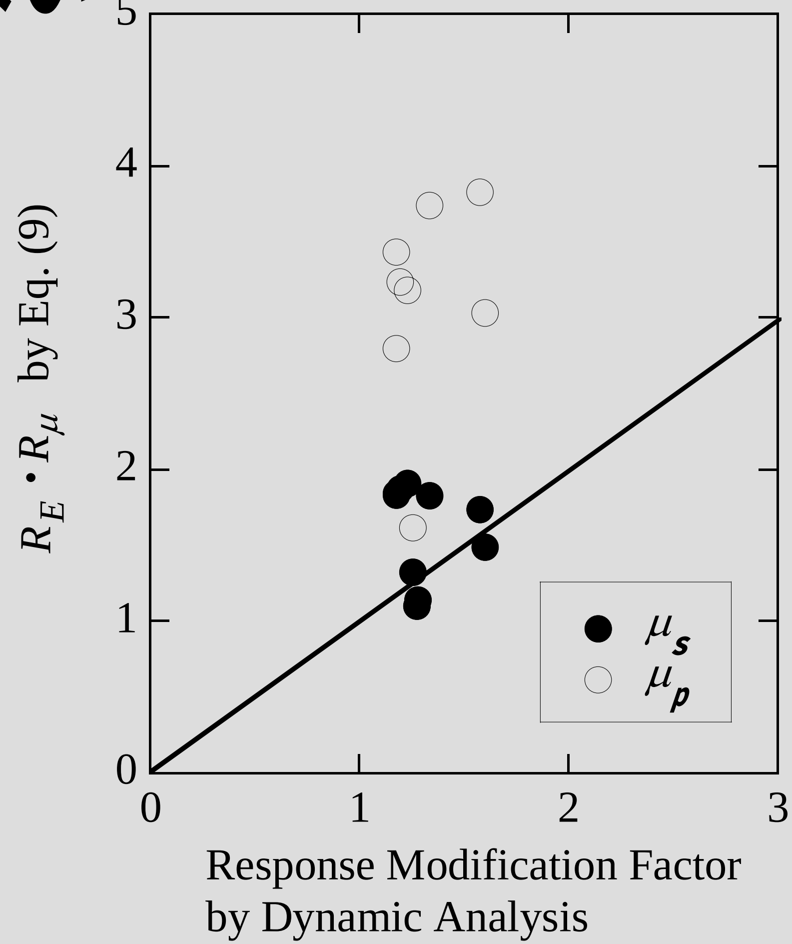


System



Response Modification Factor should be Evaluated Based on not Column Ductility Factor but System Ductility Factor

荷重低減係数は構造系じん性率を用いて評価しなければならない



Seismic Isolation with Limited Increase of Natural Period (Menshin Design)

長周期化抑制型免震設計

Menshin Design
免震設計

Seismic Isolation
免震設計

Increase of the natural period

Increase of the energy dissipation

Menshin Design
長周期化抑制型免震設計

Limited increase of the natural period

Increase of the energy dissipation

Distribute lateral force to as many substructures as possible

Favorable Implementations of Menshin Design

- Super multi-span continuous bridges
- Damage control of bearings and piers
- Seismic retrofit of existing bridges
- Deck connection to make simply supported decks to multi-span decks

Design Codes for Menshin Design

- 1989 Guideline for Menshin Design of Highway Bridges
- 1992: Manual of Menshin Design of Highway Bridges
- 1995: Guide Specifications for Design of Highway Bridges that suffered Damage in the 1995 Hyogo-ken nanbu Earthquake
- 1996: Part V Seismic Design, Design Specifications of Highway Bridges
    - ✓First stipulations in the mandate code
- 2002: Part V Seismic Design, Design Specifications of Highway Bridges

Part V Seismic Design
Design Specifications of Highway Bridges

Japan Roads Association, 1996

Highway bridges with span length less than 200m

About 2000-3000 new bridges per year

- Part I Common Part
- Part II Steel Bridges
- Part III Concrete Bridges
- Part IV Foundations
- Part V Seismic Design

Part V Seismic Design
Design Specifications of Highway Bridges

Merit of Seismic Isolation
免震設計のメリット

- Enhance the seismic performance **耐震性の向上**
- Decrease construction cost **建設コストの低減**

LRB & HDR are frequently implemented as one of elastomeric bearings without taking benefit of energy dissipation into design
免震設計をしないで、通常の耐震設計に基づき、ＬＲＢ、ＨＤＲを使用した橋梁も多い。

LRB & HDR are widely used for distributing the seismic lateral force to as many substructures as possible
地震時反力分散構造でＬＲＢやＨＤＲを使用