Response Modification of Urban Infrastructure
都市施設の免震設計

第5章　橋梁の免震設計(1)
Chapter 5 Design of Isolated Bridges (1)

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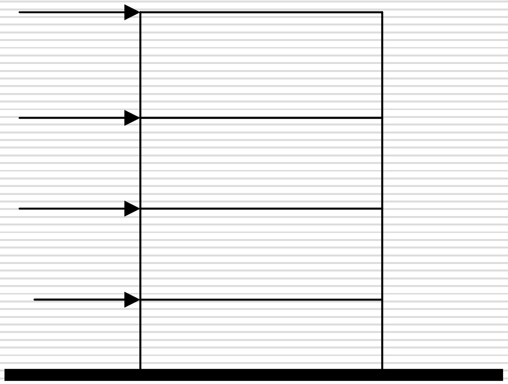
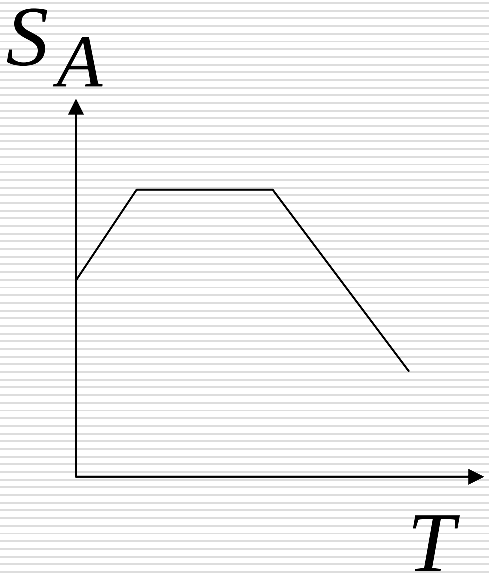
5.1 Important Knowledge on the Nonlinear Structural Response

1) Force Reduction Factor
荷重低減係数

(1) Definition of Force Reduction Factor





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

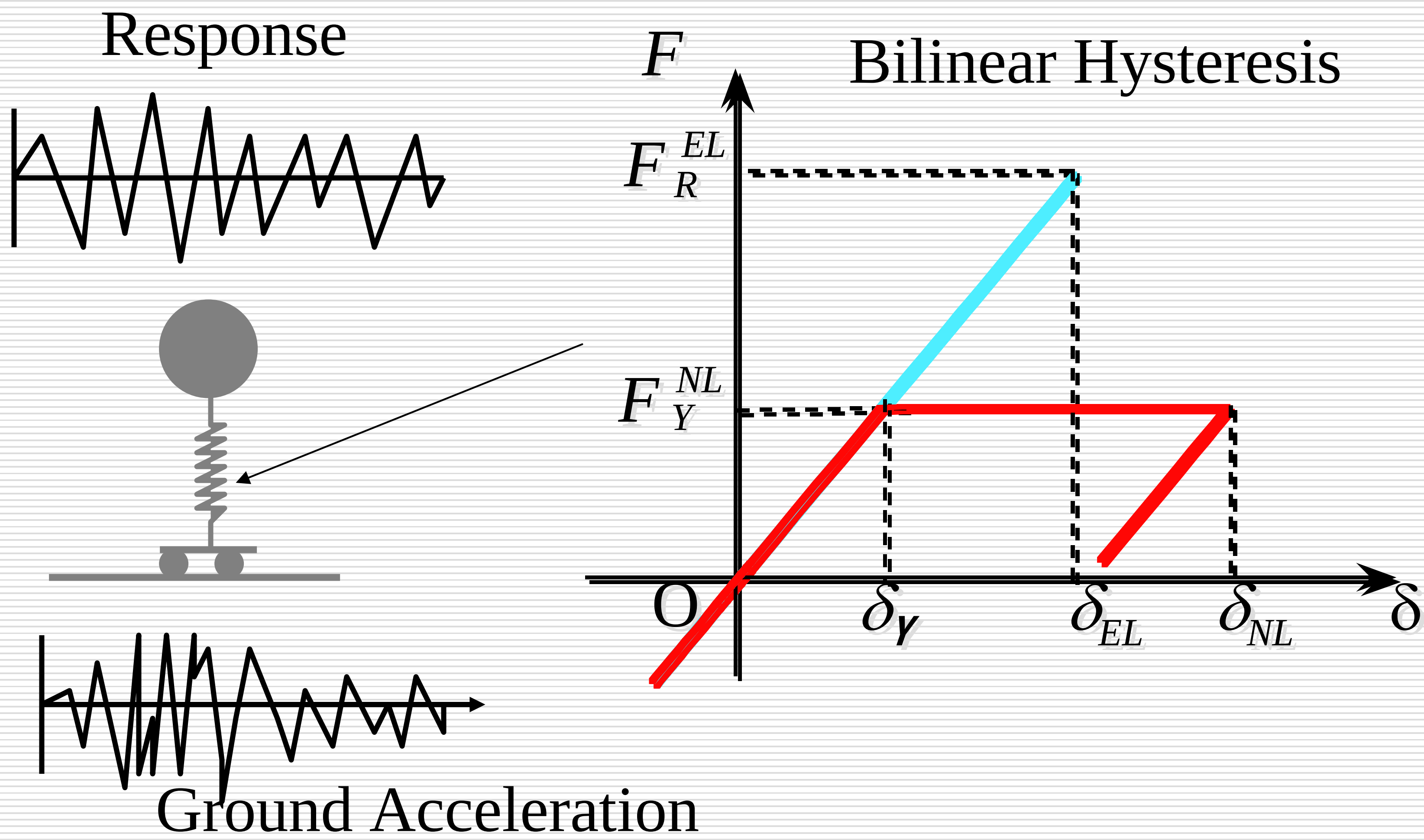
Elastic Inertia Force

$$F_{EL} = mS_A$$

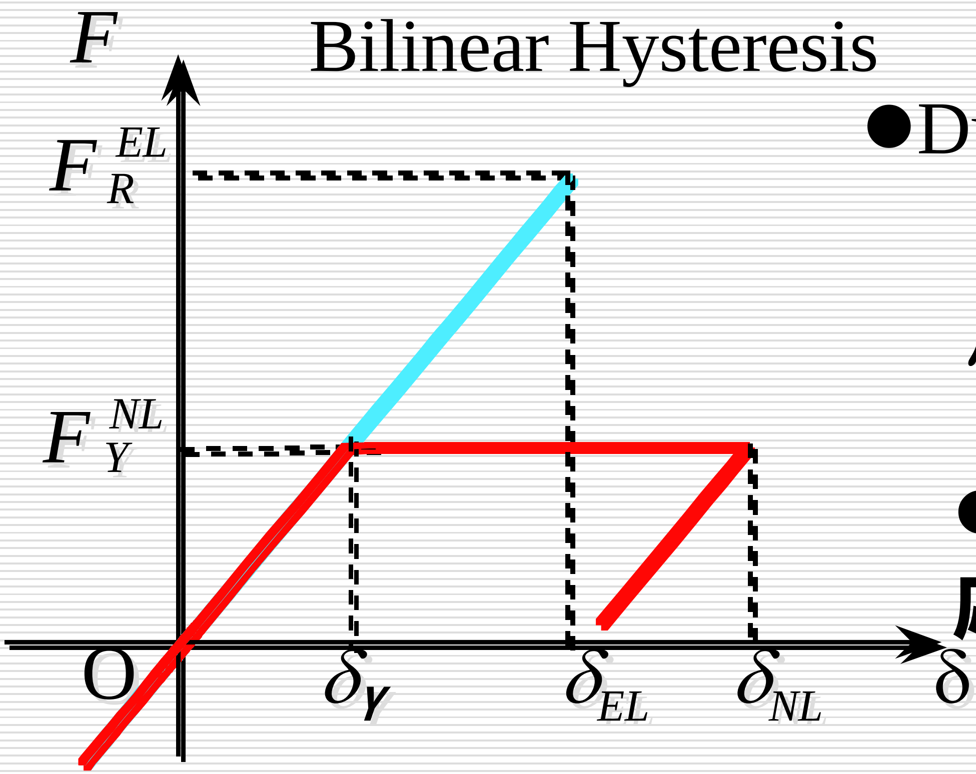
Inertia Force considering nonlinear behavior of a structure

$$F_{NL} = ??$$

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



(2) Ductility Factor　じん性率



●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)

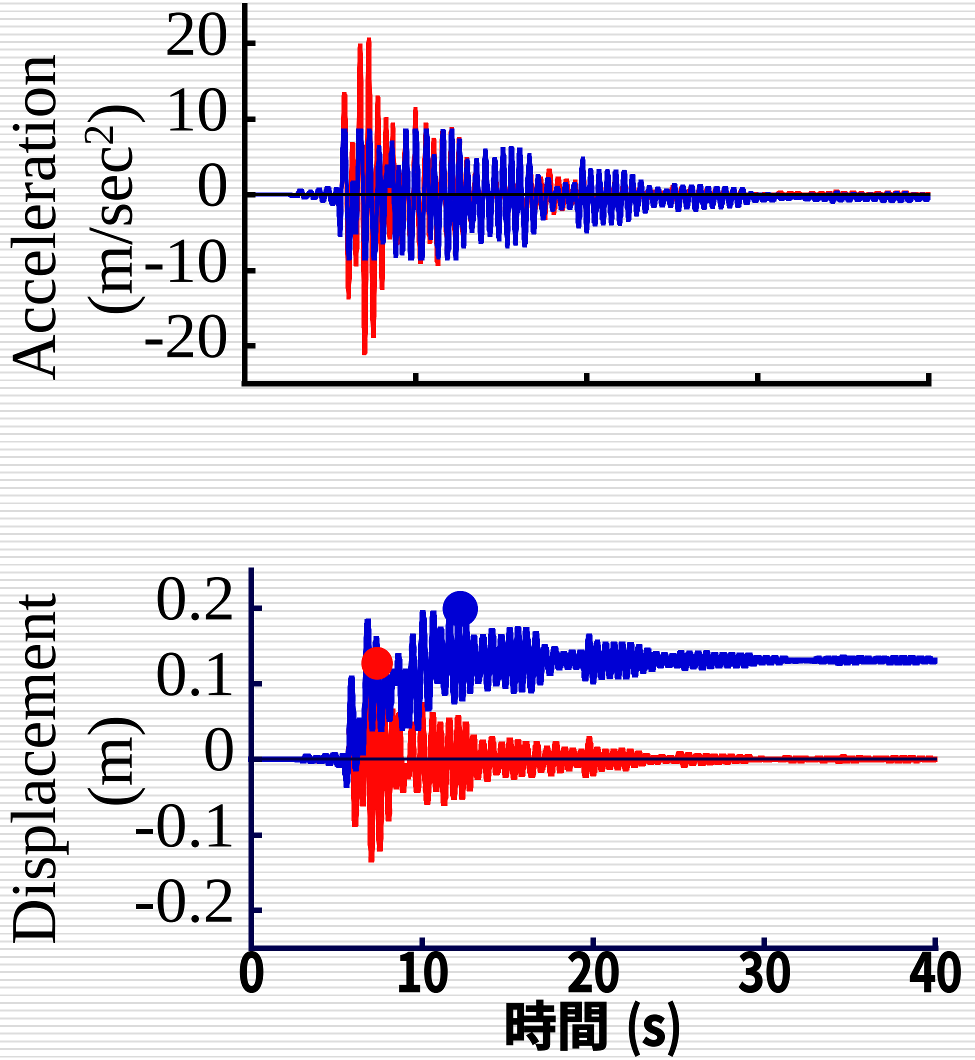
δ_{NL} : Maximum nonlinear response displacement

(3) Target Ductility Factor 目標じん性率

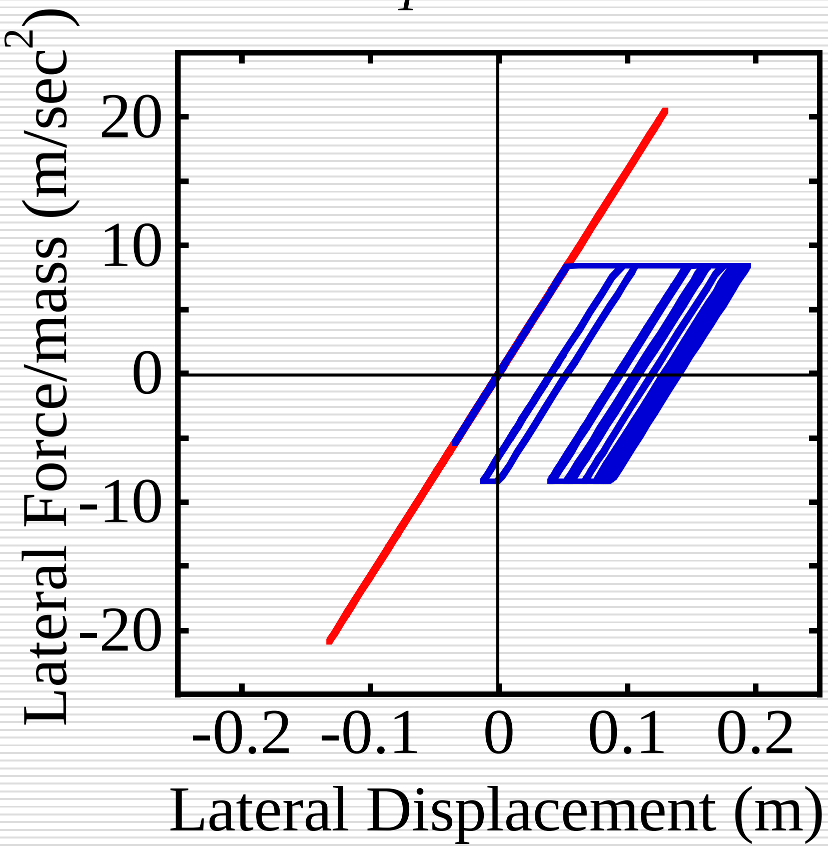
- Target ductility factor is a response ductility factor which is anticipated to occur in design
- If response ductility factor is less than the target ductility factor, designed structure must show expected performance
- If response ductility factor is larger than the target ductility factor, designed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

(4) Example of Nonlinear Response of a Single Degree of Freedom Oscillator

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



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



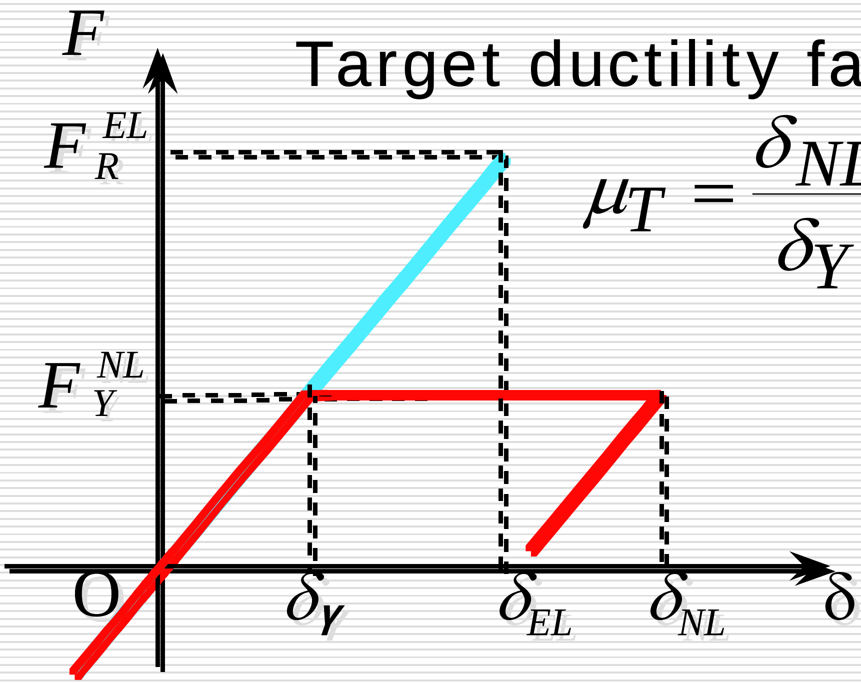
(5) Force Reduction Factor 荷重低減係数

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

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



- ✓ Force reduction factor
- ✓ Response modification factor (US)
- ✓ q-factor (EC)
- ✓ R-factor
- ✓ ..

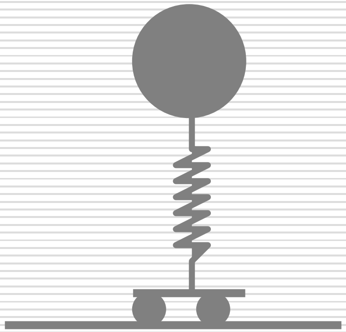
(6) How is the Force Reduction Factor used in Seismic Design?

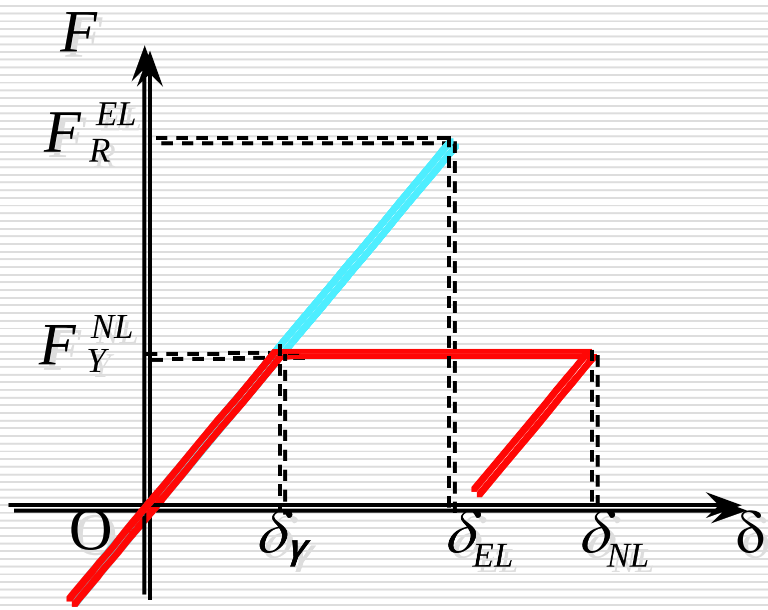
Elastic force can be approximately estimated as

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

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

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





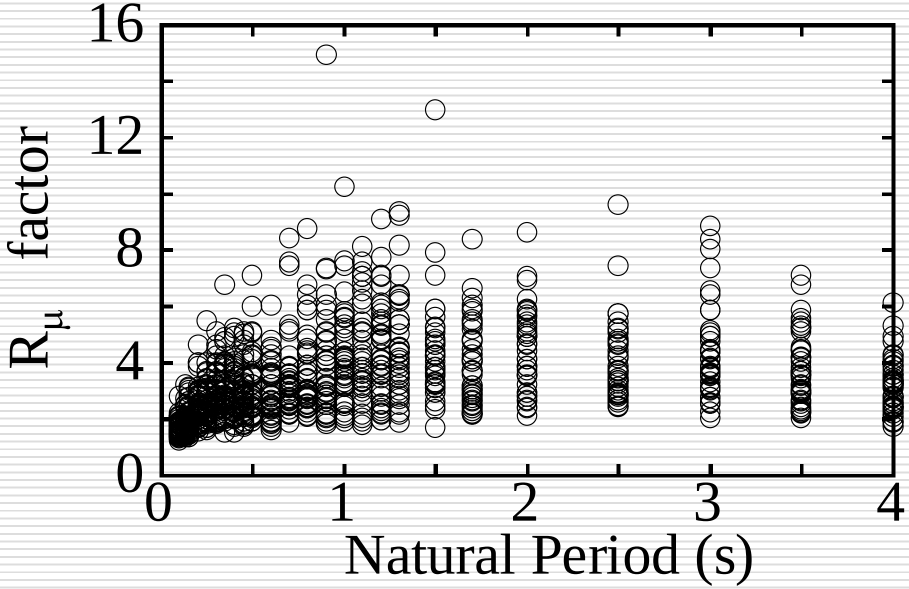
(7) Characteristics of Force Reduction Factor
Analysis based on 70 Free-Field Ground Acceleration Records

Moderate Soils

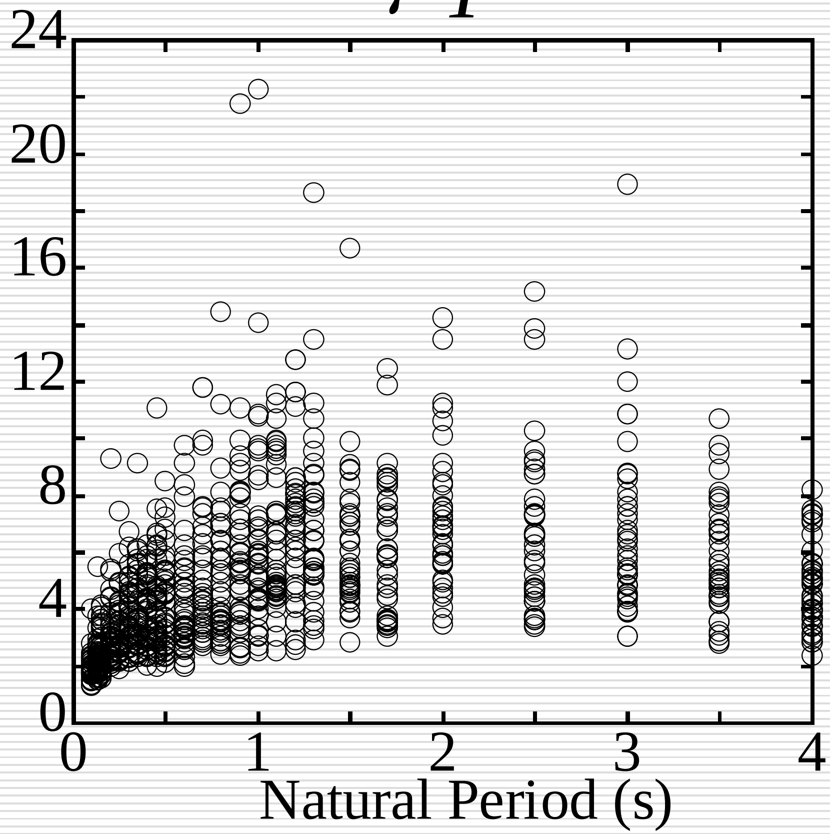
$\xi_{NL} = 0.02$

$\xi_{EL} = 0.05$

$\mu_T = 4$



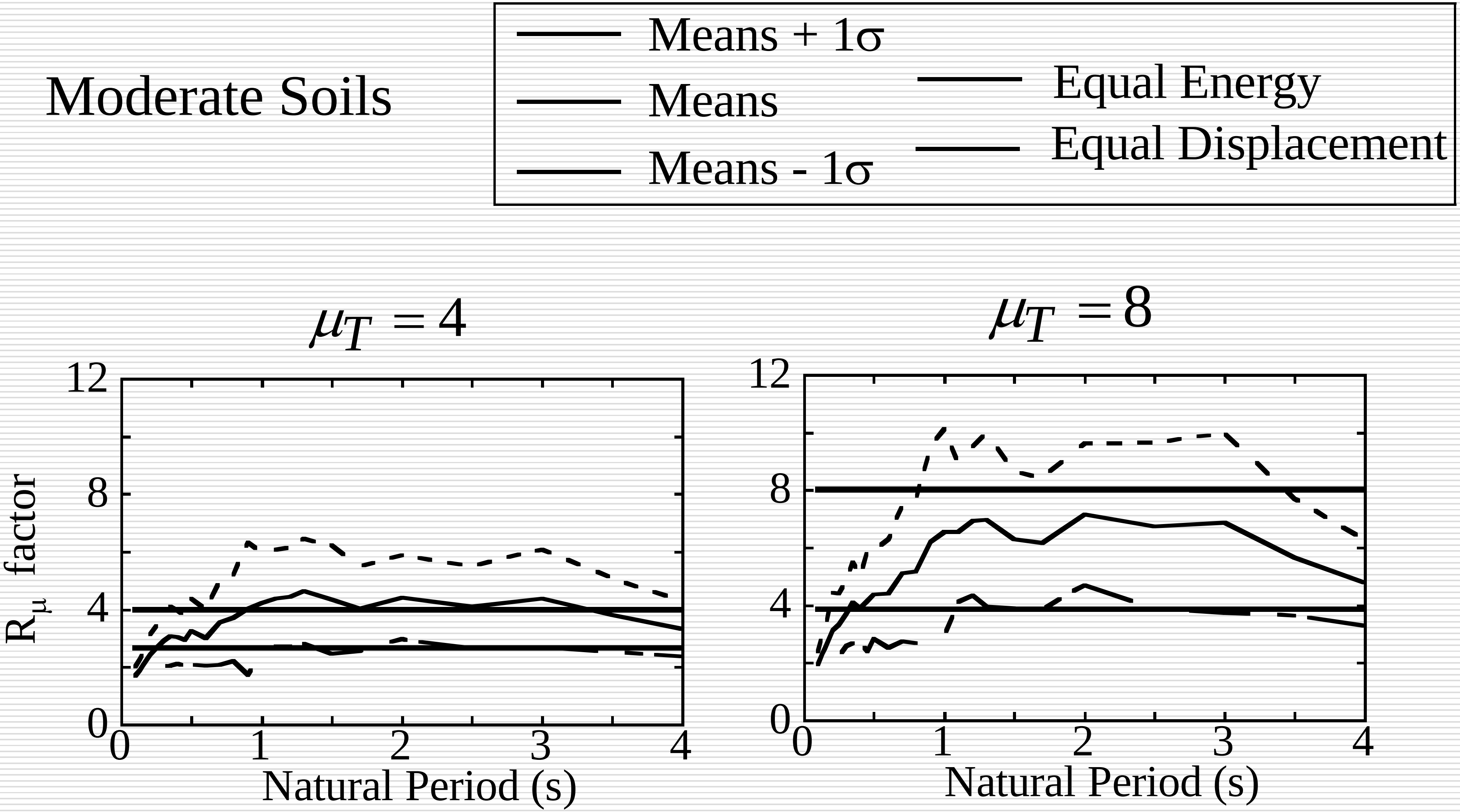
$\mu_T = 6$



Watanabe & Kawashima (2002)

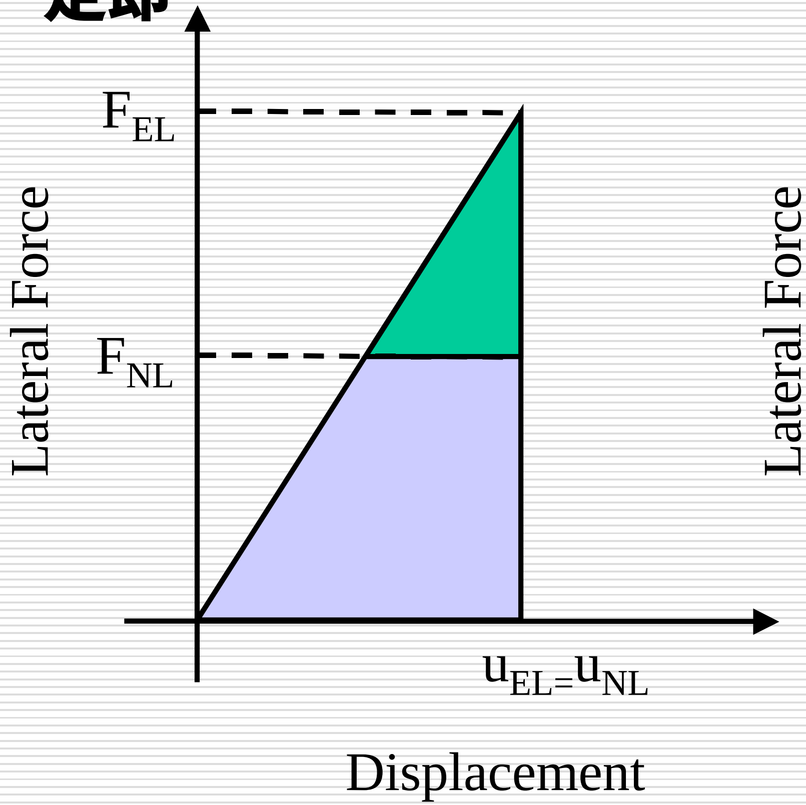
Large Scattering of Force Reduction Factor depending on Ground Motions

Moderate Soils



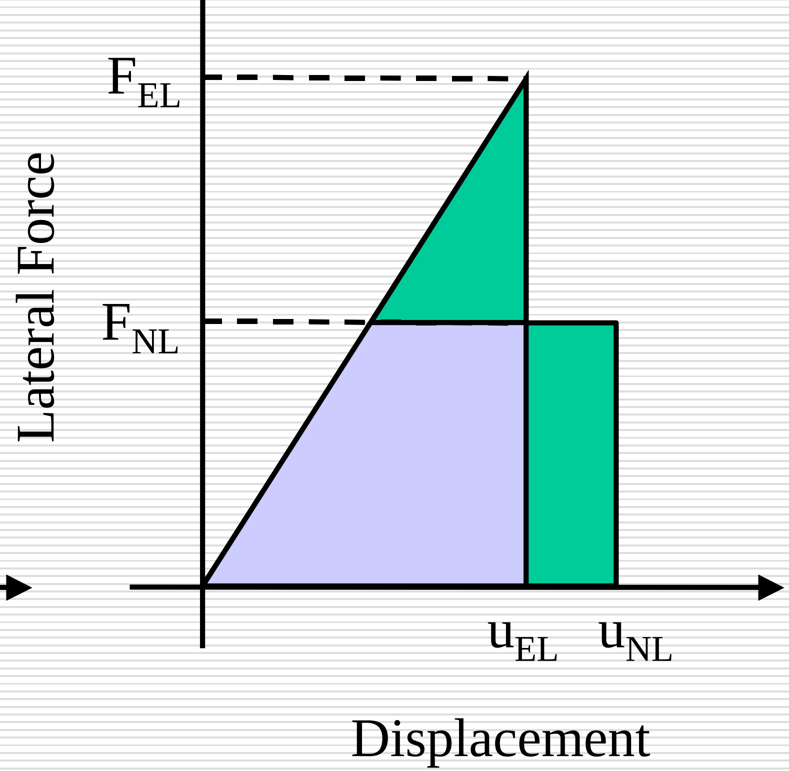
(8) Approximate Estimates of the Force Reduction Factors 荷重低減係数の推定法

Equal Displacement Assumption
変位一定即



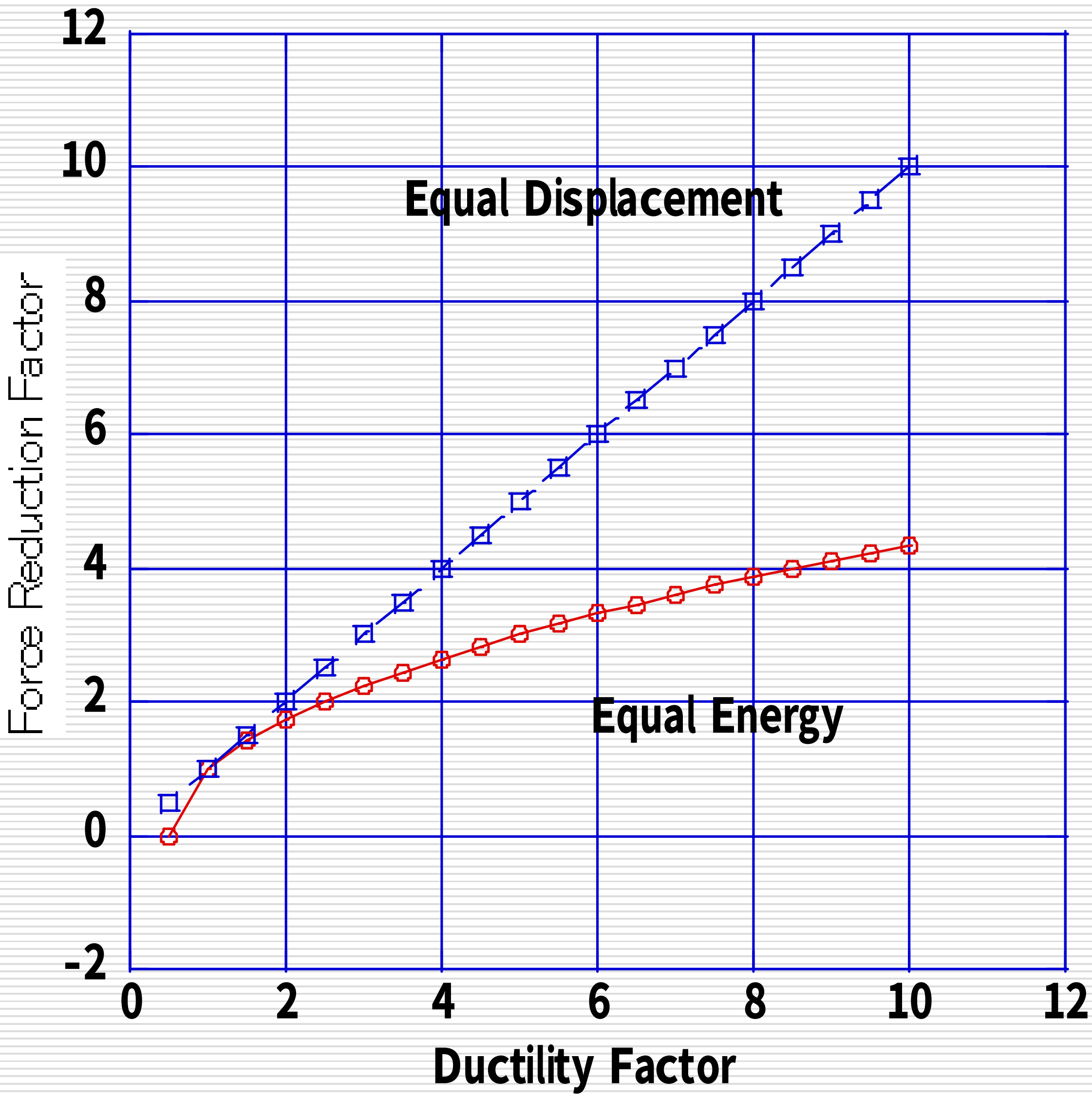
$$R_\mu = \mu$$

Equal Energy Assumption
エネルギー一定即



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

Conservative Estimation is provided by the Equal Energy Concept than the Equal Displacement Concept

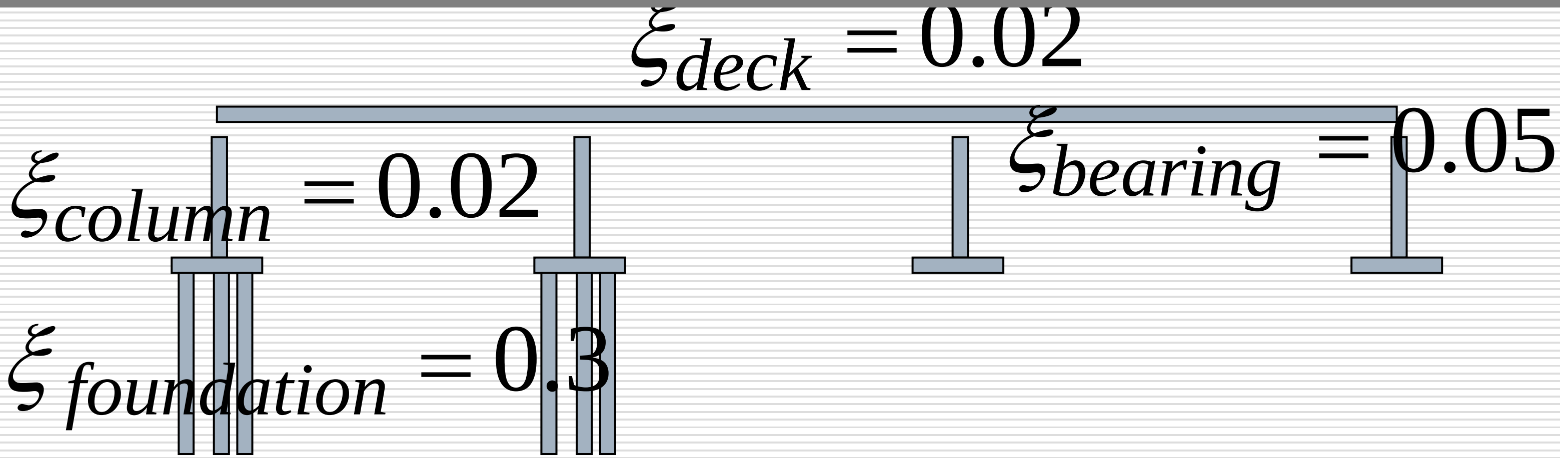


(9) Problems involved in the Current Evaluation of Force Reduction Factor 現在の荷重低減係数の問題

- Effect of unloading path **除荷剛性の影響**
- Response under near-field ground motions with long pulses **長周期パルス地震動を有する断層近傍地震動下における構造物の非線形応答**
- Effect of bilateral ground motions **水平2方向地震動の影響**
- Effect of vertical ground motions **上下方向地震動の影響**
- ....

2) How can we determine the modal damping ratios of a structural system consisting of structural components with different damping ratio? 橋梁系のモーダル減衰定数をどのように推定できるか

(1) Damping Ratio of Structural Components and Modal Damping ratio of a Structural System



●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.

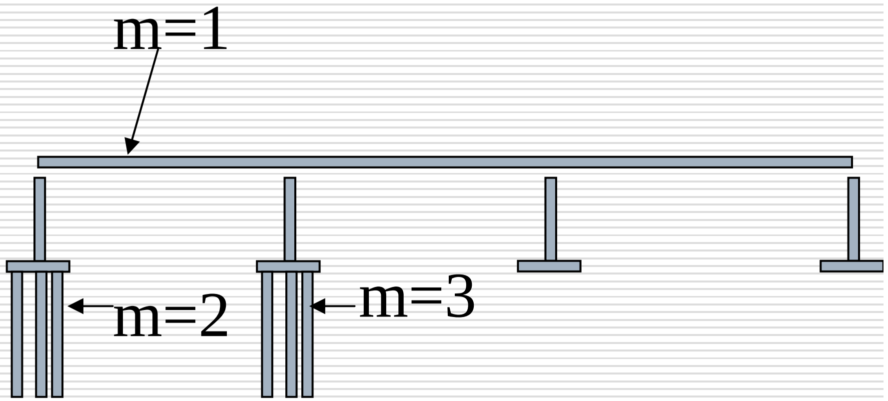
How can we determine the modal damping ratios by assigning damping ratios of each structural components? (continued)

- 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

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

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

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



where

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

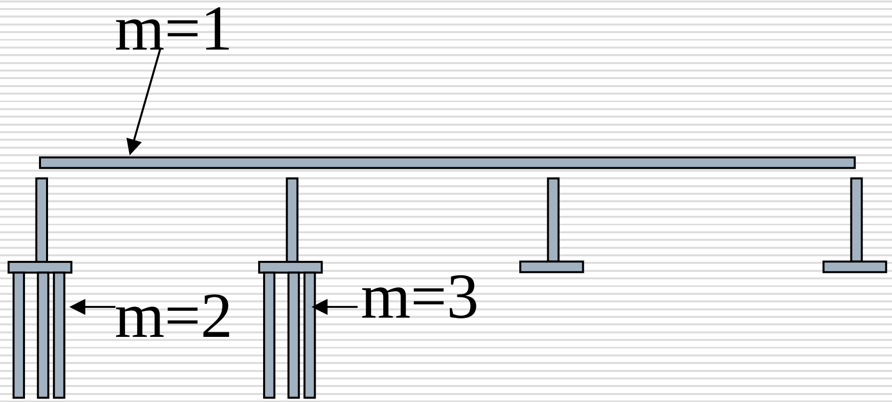
k_m : stiffness matrix of m-th element

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

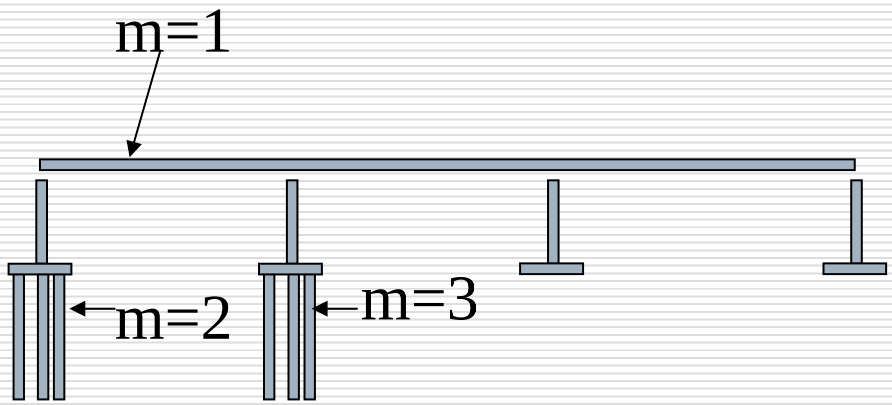
$$U_{km} = \frac{1}{2} f_{km}{}^T u_{km}$$

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

Therefore, the total energy dissipation of the system is

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

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



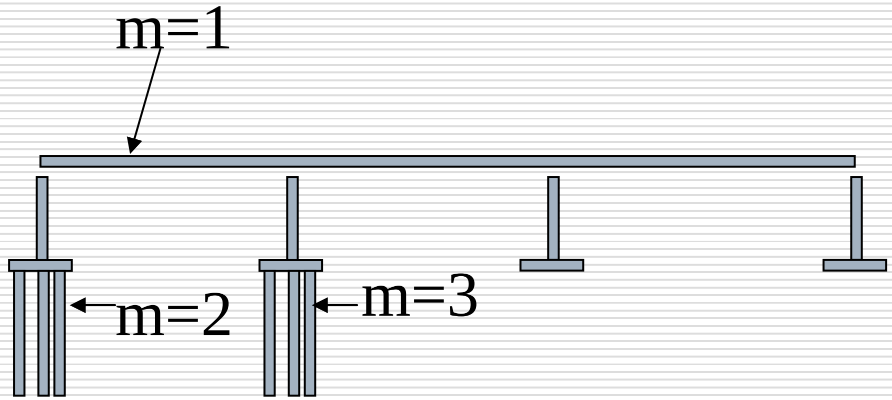
$$= \frac{\sum_{m=1}^{n} \xi_{km} \cdot \phi_{km}^{T} \cdot \mathbf{k}_m \cdot \phi_{km}}{\sum_{m=1}^{n} \phi_{km}^{T} \cdot \mathbf{k}_m \cdot \phi_{km}}$$

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

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

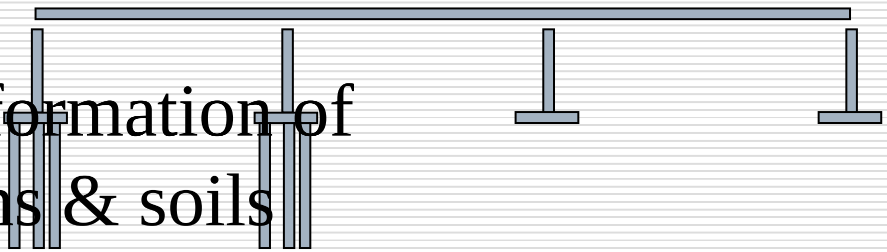
$$\xi_k = \frac{\sum_{m=1}^{n} \xi_{km} \cdot \boxed{\phi_{km}^T \cdot \mathbf{m}_m \cdot \phi_{km}}}{\sum_{m=1}^{n} \boxed{\phi_{km}^T \cdot \mathbf{m}_m \cdot \phi_{km}}} \tag{2.7}$$

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



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

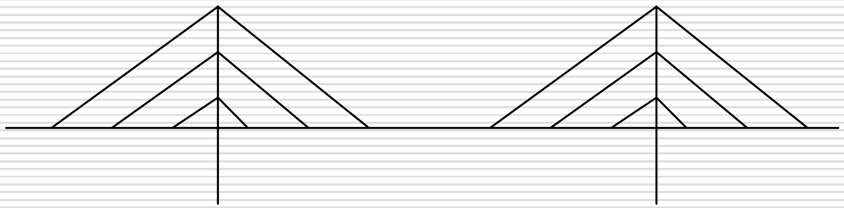
●Damping ratios of the structural components where large strain energy is developed are emphasized in the strain energy proportional method.



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

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

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



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

5.2 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

(1)Evaluation of System Damping Ratio
(1) 構造全体系の減衰定数の評価

Response modification factor resulting from enhanced energy dissipation capacity

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

Evaluation of first mode damping ratio based on energy proportion damping

Damping ratio of the k-th structural component

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

Eq. (2.6)

(1)Evaluation of System Damping Ratio (continued)
(1) 構造全体系の減衰定数の評価

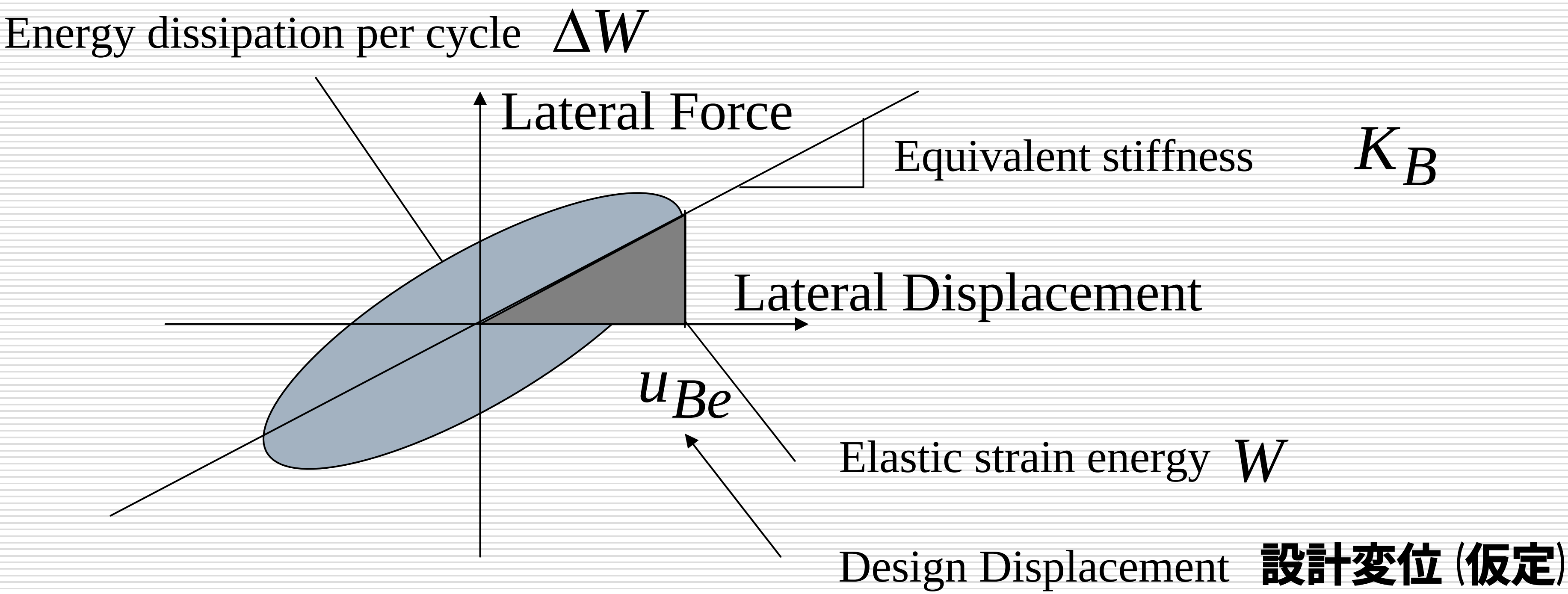
Evaluation of the First Mode Damping Ratio based on the Energy Proportion Damping Method

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

(2) Evaluation of Energy Dissipation of Isolators and Dampers (2) 免震装置の減衰定数の評価



Equivalent Stiffness
等価剛性

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

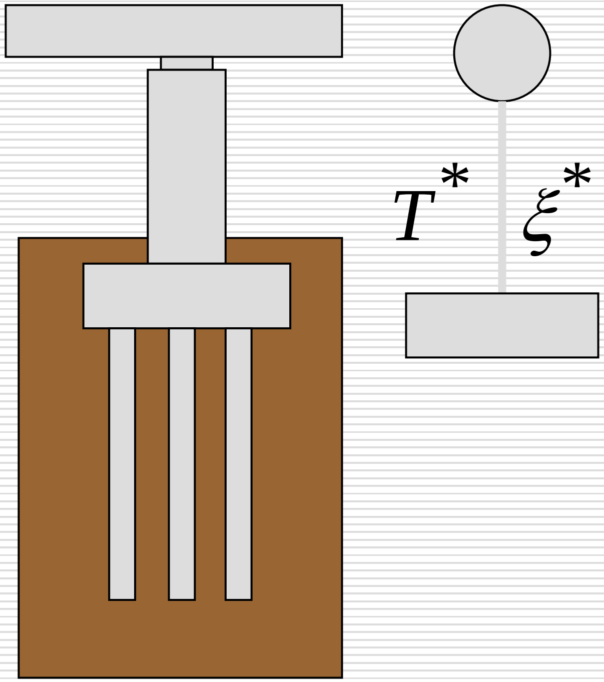
Equivalent Damping Ratio
等価減衰定数

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

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

1)Evaluation of Inelastic Lateral Force Demand for a Fixed Base Bridge
一般橋に対する非線形地震力の算出

(1) Evaluate Inelastic Lateral Force Demand using the Force Reduction Factor



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

Response modification factor

荷重低減係数

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

(2) 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 is assumed as

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

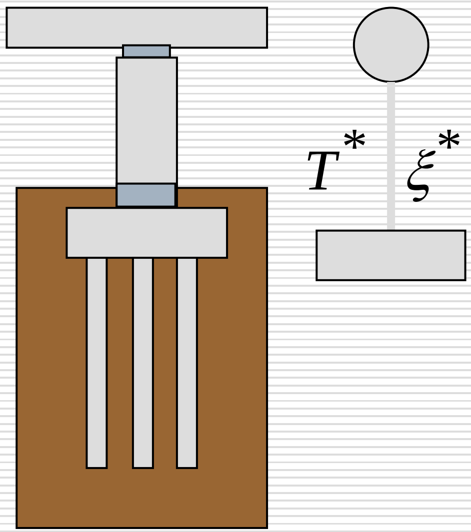
Design displacement ductility factor
設計じん性率

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

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

2) Evaluation of Inelastic Lateral Force Demand for an Isolated Bridge
2) 免震橋に対する非線形地震力の算出

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**

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

$$R_E = c_D(\xi_1)$$
$$= \frac{1.5}{40 \cdot \xi_1 + 1} + 0.5$$

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

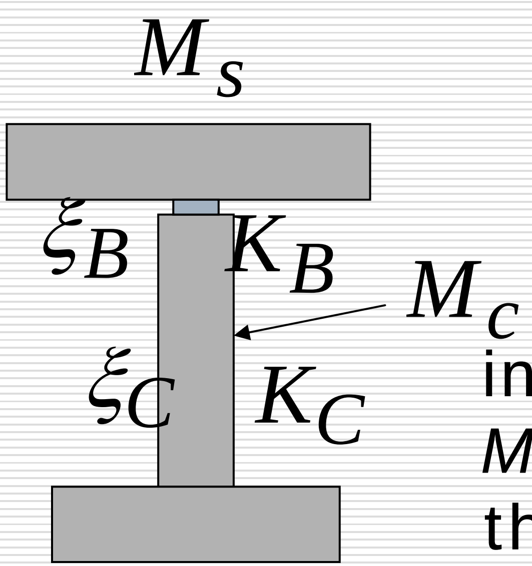
Since $\mu_{Ia} \approx (\geq) \mu_I$

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

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

(1)Determine the fundamental (the first) natural period of a bridge system

(1) 橋梁システムの基本固有周期の算定



$$T = 2\pi\sqrt{\frac{M}{K}}$$

where,

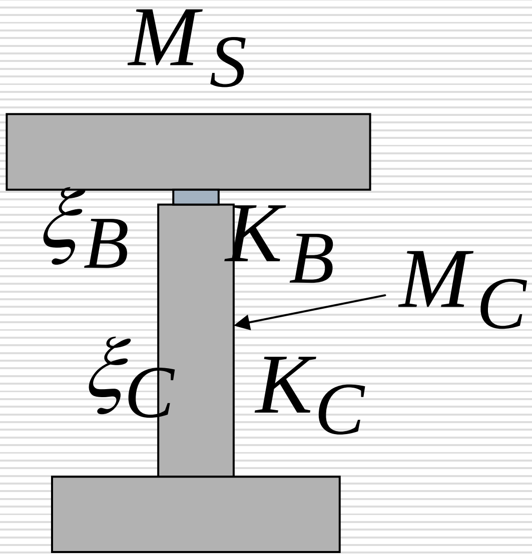
$$M = M_S + aM_C$$

in which, M_S: mass of a superstructure, M_C: mass of a column which supports the superstructure, and a: coefficient representing the degree of contribution of column (a=0.3)

(1)Determine the fundamental (the first) natural period of a bridge system (continued)

(1) 橋梁システムの基本固有周期の算定(No. 2)

$$T = 2\pi\sqrt{\frac{M}{K}}$$



K: total stiffness of the system and is give by

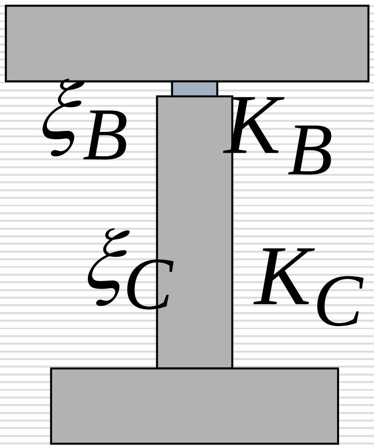
$$K = \frac{k_C k_B}{k_C + k_B}$$

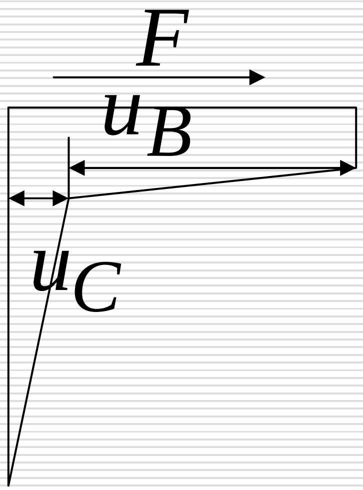
in which k_C: column stiffness, and k_B: bearing stiffness.

(2) Determine an approximate fundamental natural mode shape based on a static displacement distribution under a dead load. Effect of the foundations is disregarded here for simplicity

(2) 死荷重を受けた構造物の静的変位分布は基本固有震動モードを近似することを利用して、基本固有振動モードを求める

Based on Rayleigh Ritz method,





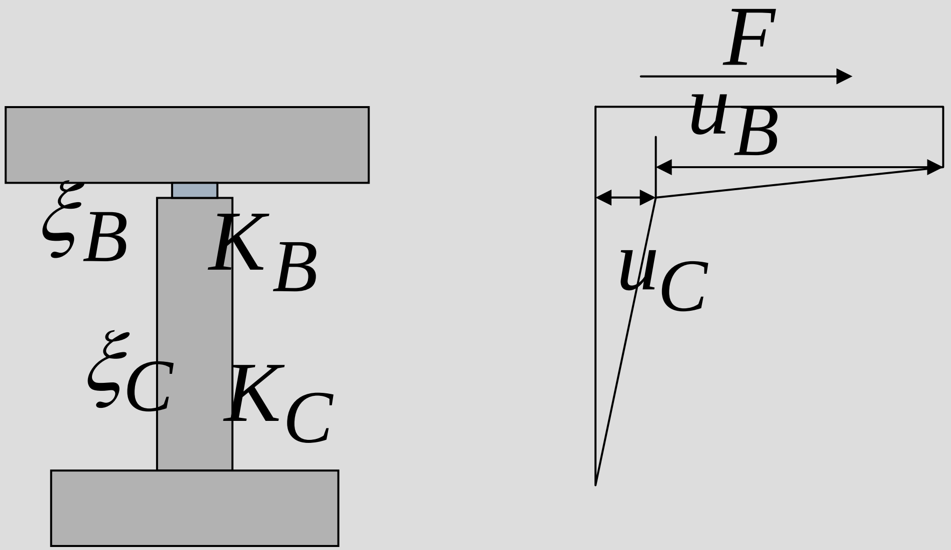
$$u_C = \frac{F}{K_C}$$

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

$$K_C \approx \frac{3EI}{l^3}$$

in which *EI* represents the moment of inertia of a column

(3) Evaluate strain energy of the main structural components (a column and an isolator in this example)



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

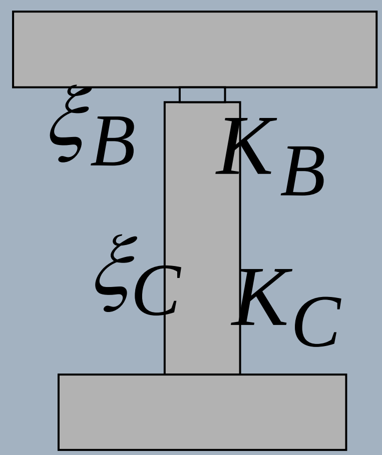
$$u_B = \frac{F}{K_B}$$

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

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

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

(4) Evaluate the system damping ratio for the fundamental mode (First modal damping ratio)
(4) 基本固有振動モードに対する構造系減衰定数を求める (1次モード減衰定数)



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

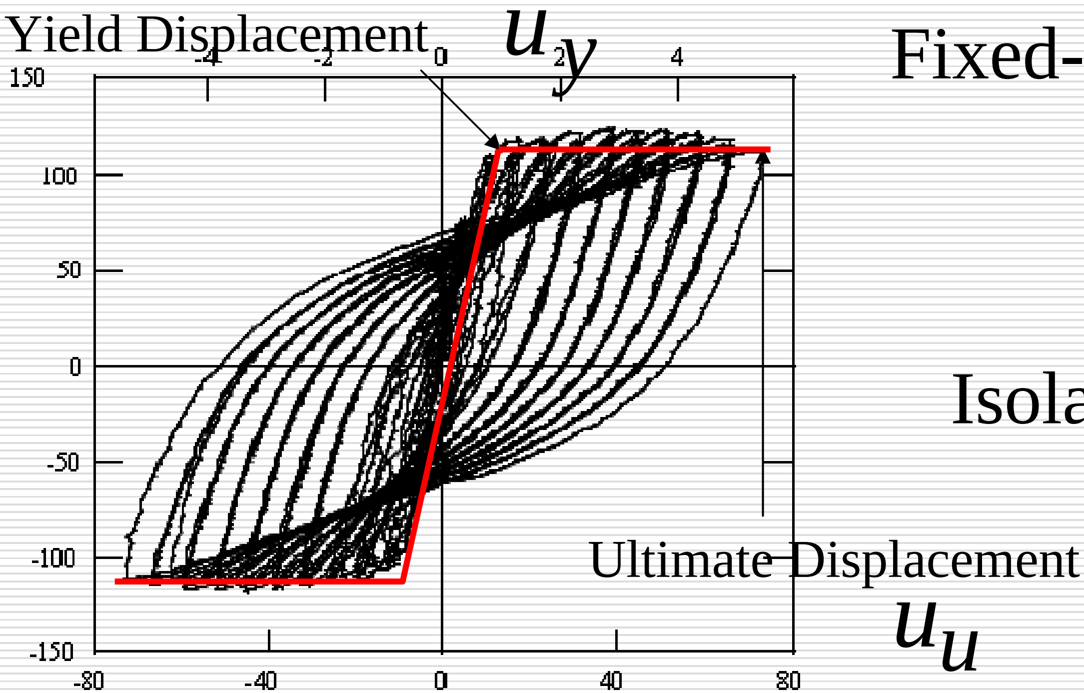
$$E_B = \frac{1}{2} K_B u_B{}^2$$

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

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

(5) Evaluate the Design Ductility Factor of the Column
(5) 設計じん性率 (許容じん性率)

Design response ductility factor of a pier



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

Damage Control of Columns in Isolated Bridges

構造系の損傷限界

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

$$\alpha_m = 2\alpha$$