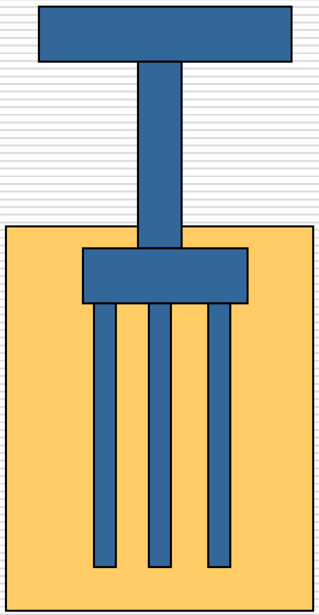
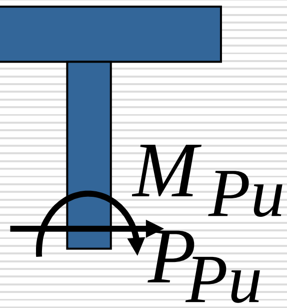
Seismic Design of Foundations

Seismic Design of Foundations

- Seismic design of foundations are usually conducted separately from the seismic design of piers & superstructures.

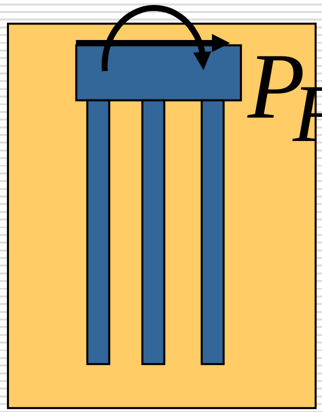
- Capacity of the piers is imposed to the foundations as the force demand as





$$P_u = M_u / h$$

$$M_F = \phi M_{Pu}$$

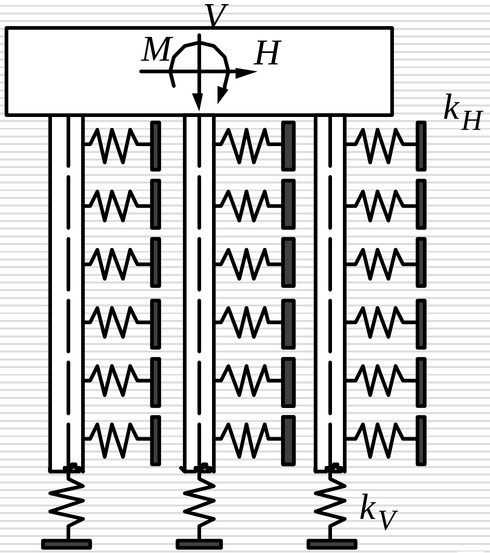


$$P_F = \phi P_{Pu}$$

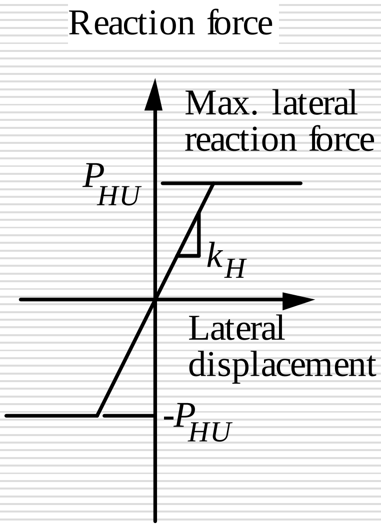
Seismic Design of Foundations (continue)

- Pushover analysis is conducted for the foundations by imposing M_F & P_F
- Capacity of the piles & footings (yield & ultimate) is determined similar way with the piers & columns. Response under the design force must be smaller than the design response values (design ductility factor etc.)
- Capacity of surrounding ground is determined based on the soil properties & overburden pressure

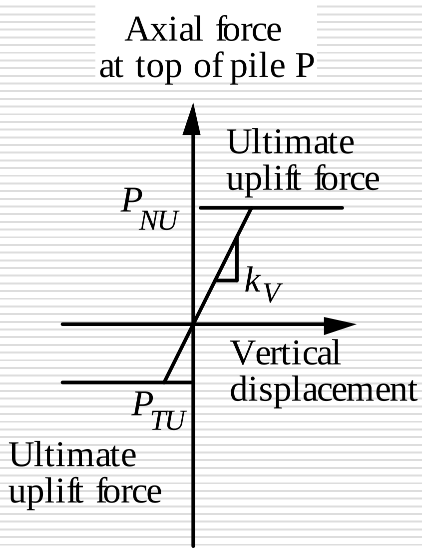
Seismic Design of Foundations (continue)



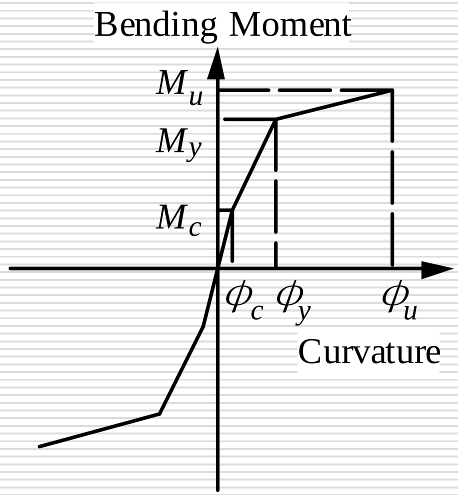
Lateral Force



Vertical Force



Moment



- Definition of Yield
  - ✓all piles yield, or
  - ✓compression of piles on a same line reaches the strength of soils

Seismic Design of Foundations (continue)

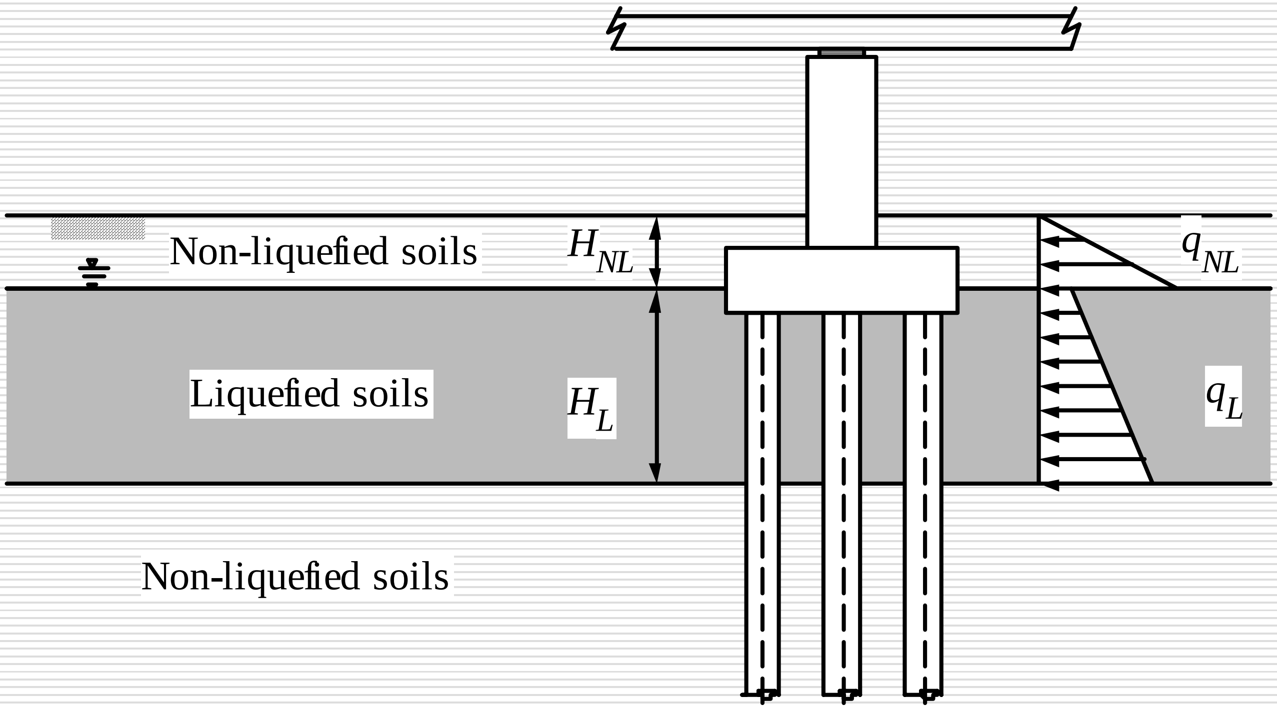
- Particular attention is paid for soils vulnerable liquefaction & lateral spreading due to liquefaction

- Soil spring stiffness is weakened depending on the degree of liquefaction & depth when liquefaction occurs

F_L-value	Depth x from Ground Surface (m)	Multiplier for soil strength	
		R<0.3	R>0.3
1/3	10	0	1/6
	10<x<20	1/3	1/3
2/3	10	1/3	2/3
	10<x<20	2/3	2/3
1	10	2/3	1.0
	10<x<20	1.0	1.0

Seismic Design of Foundations (continue)

- Particular attention should be paid when lateral spreading occurs.
- Soil-fluid force is imposed to the foundation in design



Analytical Methods

- Elastic Static Analysis (ESA)
- Elastic Dynamic Analysis (EDA)
- Inelastic Static Analysis (ISA)
- Inelastic Dynamic Analysis (IDA)

Minimum Required Analysis

Japan Road Association (1996 & 2002)

Category		Function Evaluation	Safety Evaluation
Bridges with Simple Responses		ESA	ISA
Bridges with Complex Responses	Static Analysis is Applicable	ESA and EDA	ISA and IDA
	Static Analysis is not applicable	EDA	IDA

Minimum Required Analysis (continued)

ATC 32 & Caltrans (1999)

Importance	Configuration	Function Evaluation	Safety Evaluation
Ordinary Bridges	Type-I	None	ESA or EDA
	Type-II	None	EDA
Important Bridges	Type-I	ESA or EDA	ESA or EDA
	Type-II	EDA	EDA, ISA and IDA

Dynamic Response Analysis

Dynamic Response Analyses are Recommended for the Following Bridges

- Bridges in which plastic hinges are formed at several locations
  - ✓ Bridges supported by elastomeric bearings
  - ✓ Isolated bridges
  - ✓ Moment resisting type bridges
  - ✓Bridges supported by steel bridges
- Bridges with predominant higher modes effects
  - ✓ Bridges with long periods
  - ✓ Bridges supported by tall columns
- Bridges with complex structural responses
  - ✓ Cable stayed bridges, suspension bridges
  - ✓ Arch bridges
  - ✓ Curved bridges

Why is static analysis needed prior to dynamic analysis?

- Because we generally need a preliminary structural section (how tall, what are sections, what amount reinforcements? …….) as an original input data in the dynamic response analysis

- Because preliminary design is thus generally conducted to each structural components, such as each column, each foundation, each bearing, etc.

- Because dynamic analysis needs computer, and was more expensive than the static analysis

- Because designers are more familiar with the static analysis than the dynamic analysis

Design based on Dynamic Analysis

- Static design is easier than the dynamic response analysis, but it has a certain limitation such as
  - ✓Higher modes effect cannot be included without special treatment. The special treatment looses generality
  - ✓Bridges with multi-hinge cannot be analyzed
  - ✓Relative displacement cannot be analyzed
- Designers do not want to change the analytical methods depending on type and requirements of design, but they want to use the same analytical method which can be used to any type of bridges.

Design based on Dynamic Analysis (continued)

- Designers do not want to use an analytical method which needs works of the designers at several steps
- Use of computer was expensive 10 years ago, but it is virtually free. “Use computer without occupying designers” is the current direction in design
- Precise models are prepared for design to static load, active load, creep & shrinkage etc. The same models can be used in the dynamic response analysis.
- Young designers are moving toward “design based on dynamic response analysis.”

Spectral Fitted Ground Accelerations

Response Spectral Analysis based on Mode Superposition Method

- Response spectral method is still used in linear analysis, but the benefit of the spectral method has decreased in recent years, because
  - ✓Cost of computation becomes not important as the dynamic analysis softwares on PC becomes become widely used
  - ✓Nonlinear dynamic response is conducted on routine basis

Spectrum Fitting Ground Acceleration

- Ground accelerations which provide closer response to the ground acceleration with the target response spectra are sometimes used for analysis in design
- Spectral fitting ground motions give closer response to the target acceleration for linear structures. The seismic response of nonlinear structures using the spectral fitted ground motions have to be carefully evaluated

Spectrum Fitting Ground Acceleration (continued)

- There are many methods in producing spectral fitting ground accelerations. They can be grouped into two as
  - ✓Generate ground accelerations by assuming appropriate frequency dependence of amplitude & phase
  - ✓Modify existing ground acceleration
- Because the phase amplitude controls the shape of ground acceleration, it is suggested to modify the amplitude with the phase amplitude being unchanged

Computation of Spectral Fitted Ground Motions

1) Determine the target response spectrum $S_A(f,\xi)$

2) Select an appropriate ground acceleration $a_m(t)$ which has closer spectral characteristics with $S_A(f,\xi)$

3) Compute response spectrum $\tilde{S}_A(f,\xi)$ of $a_m(t)$

4) Evaluate whether $\tilde{S}_A(f,\xi)$ is close enough to $S_A(f,\xi)$ as

$$\frac{S_A(f,\xi)}{\tilde{S}_A(f,\xi)} < \varepsilon(f) \qquad (1)$$

If Eq. (1) is satisfied, stop and $a_m(t)$ provides close enough spectrum with the target response spectrum

5) If Eq. (1) is not satisfied, compute the Fourier amplitude as

$$c_k = \frac{1}{N}\sum_{m=0}^{N-1} a_m \exp\left(-i\frac{2\pi km}{N}\right) \quad k = 1,2,\cdots\cdots \qquad (2)$$

6) Compute modified Fourier amplitude as

$$C_k{}' = C_k \frac{S_A(f)}{\tilde{S}_A(f)} \qquad (3)$$

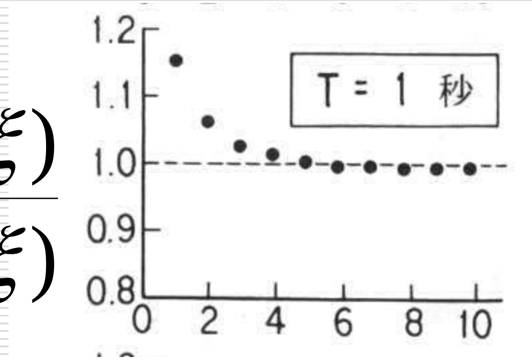
7) Inverse Fourier transform gives the corrected acceleration as

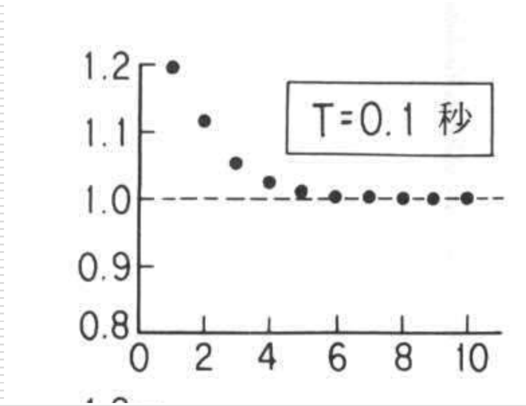
$$a_m = \sum_{k=0}^{N-1} C_k{}' \exp\left(i\frac{2\pi km}{N}\right) \qquad (4)$$

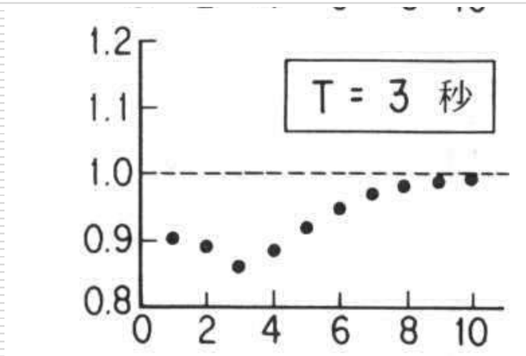
8) Go to 3)

Number of Iteration to have convergence

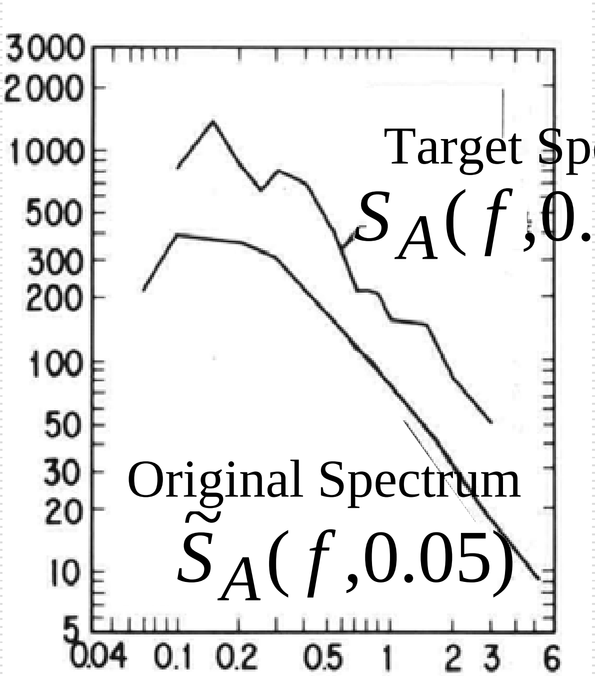
$$\frac{S_A(f,\xi)}{\tilde{S}_A(f,\xi)}$$







Number of Iteration



Target Spectrum $S_A(f,0.05)$

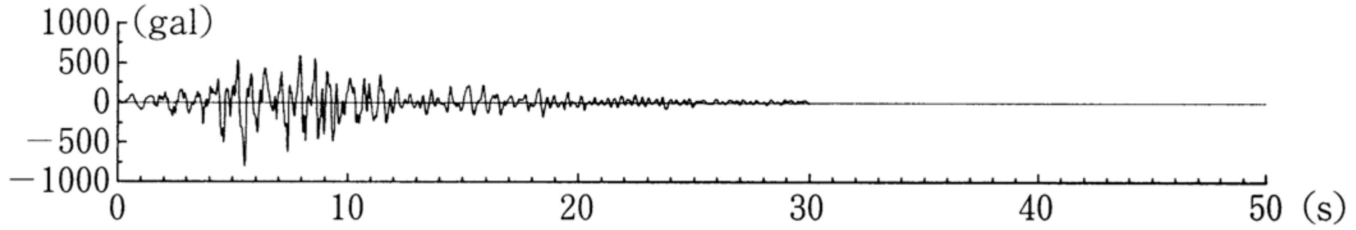
Original Spectrum $\tilde{S}_A(f,0.05)$

Response acceleration (cm/s^2)

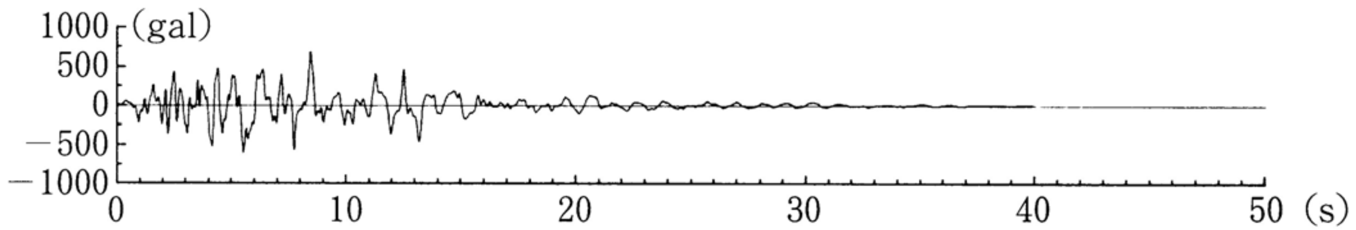
Natural Period (s)

Example of Spectral Fitted Ground Accelerations

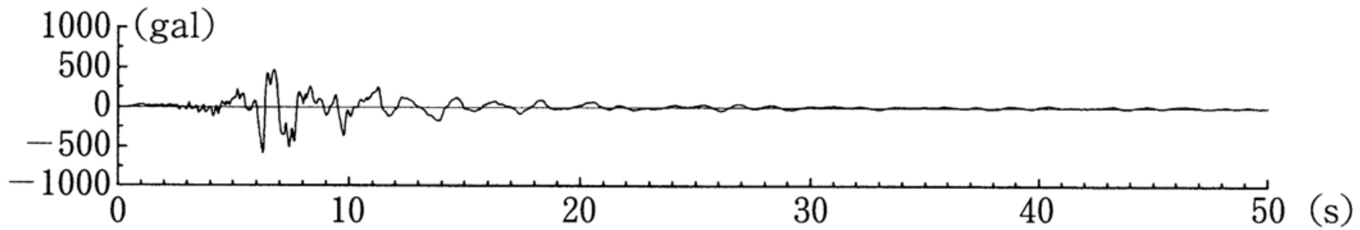
Stiff (Group I)



Moderate (Group II)



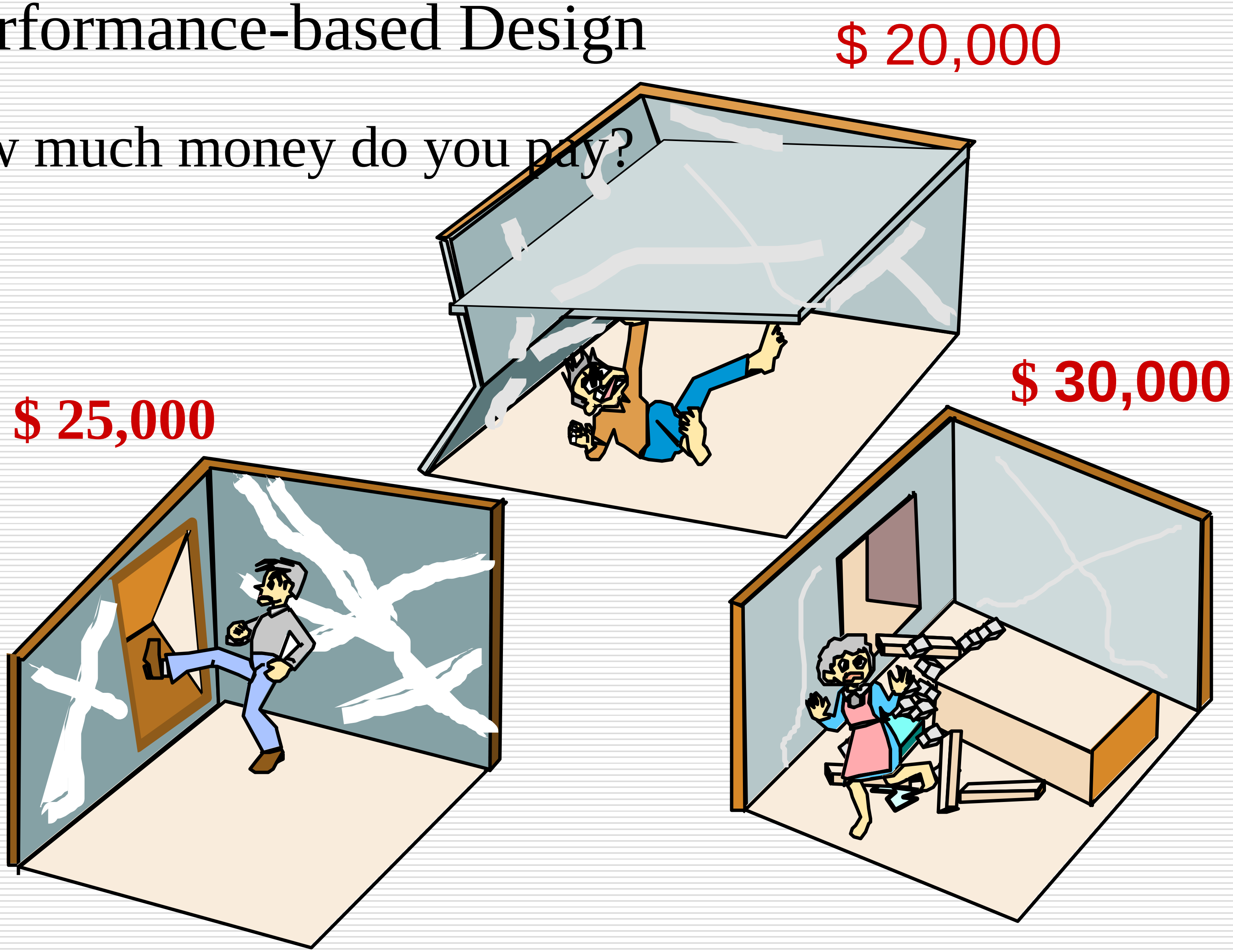
Soft (Group III)



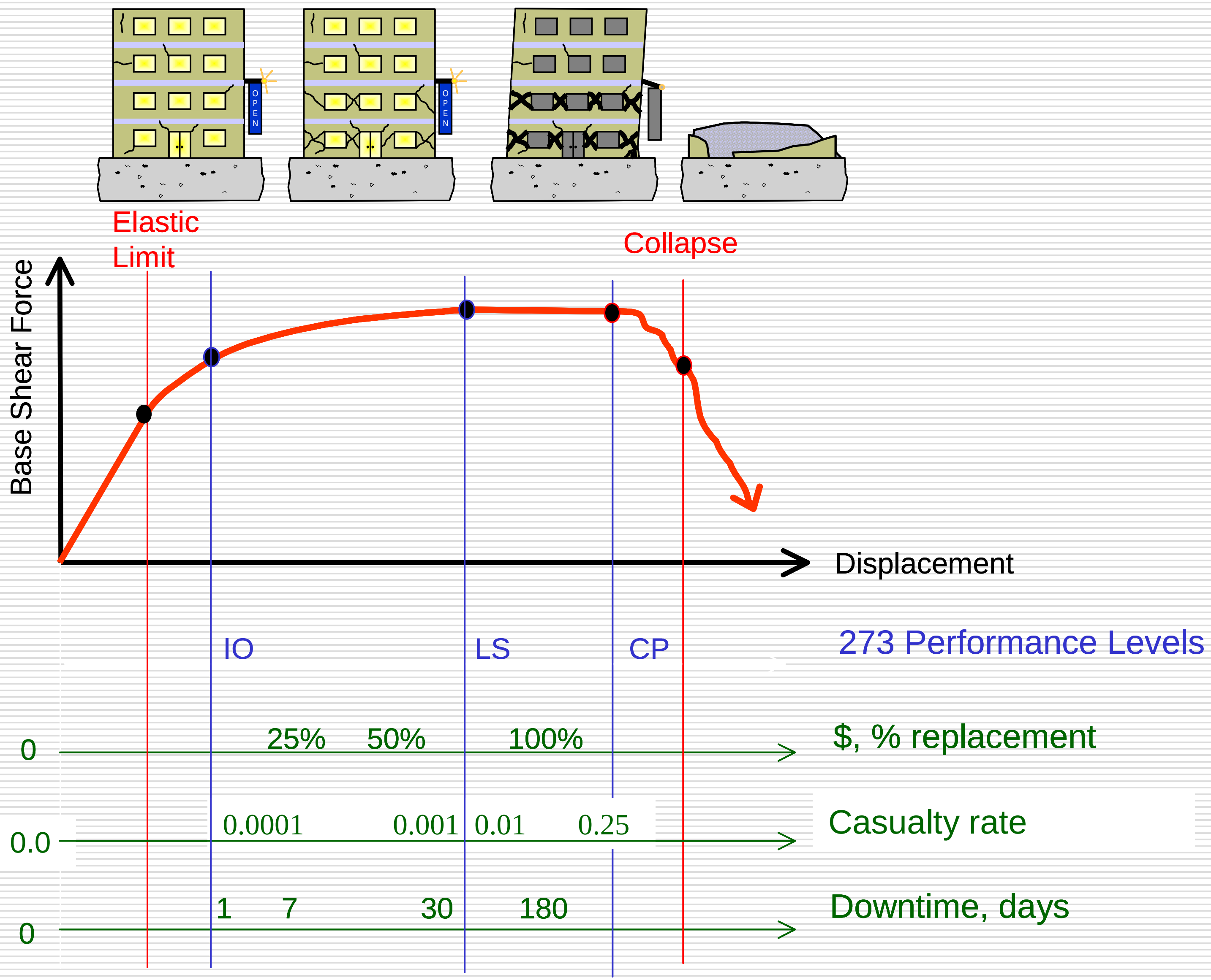
Performance-based Seismic Design

Performance-based Design

How much money do you pay?

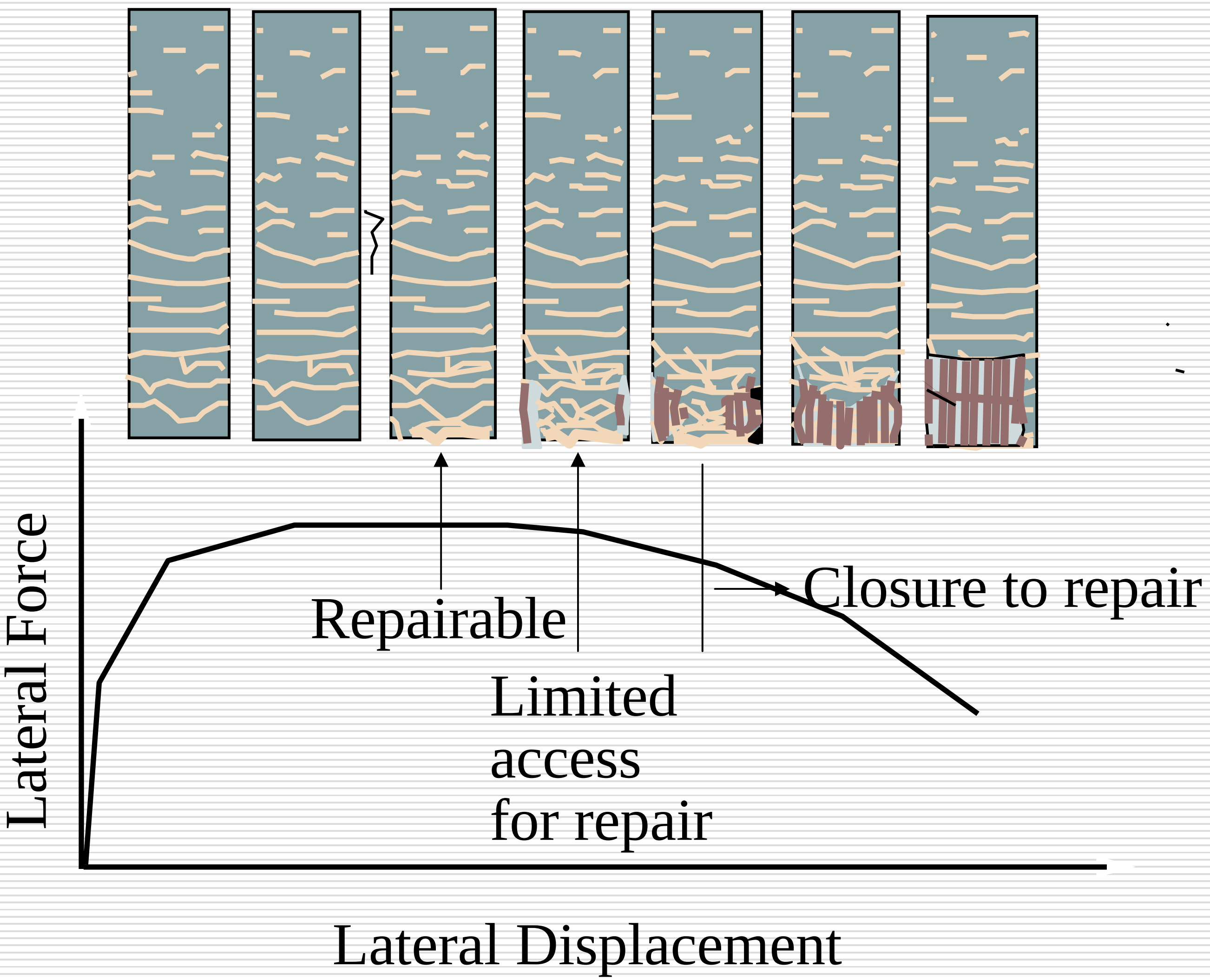


ATC-58 Next Generation PBD



After Mohele, J. (2004)

Performance of Bridge Column



There are not only 2 but many realistic performance goals in seismic design of bridges

$$\{P\} = \begin{Bmatrix} \text{Maintain Function} \\ \text{Prevent Collapse} \end{Bmatrix}$$

- the bridge must be accessed within 24 (or, 48) hours after the earthquake
- middle 2 lanes must be used for emergency light vehicles
- all lanes must be used for heavy traffic for with restriction of velocity of 20 km/h
- …..

Performance Based Seismic Design

Performance Goals vs. Design Ground Motions

$$\{P\} = [M_{PG}]\{G\}$$

Design ground motion vector

Performance matrix

Performance goals vector

For example,

$$\{P\} = \begin{Bmatrix} \text{Maintain Function} \\ \text{Prevent Collapse} \end{Bmatrix}$$

$$\{G\} = \begin{Bmatrix} \text{Function Evaluation GM} \\ \text{Safety Evaluation GM} \end{Bmatrix}$$

Notes in the Notations

- The above equation is not a standard equation, but represents relation between two quantities.
- For example, $\{P\}=[M_{PG}]\{G\}$ represents a relation between $\{P\}$ and $\{G\}$
- The same format is used in the following expressions

Response of a structure can be evaluated if ground motions are prescribed.

$$\{R\} = [M_{RG}]\{G\}$$

Design ground motion vector

Response matrix

Structural response vector

For example,

$$\{R\} = \left\{\begin{array}{l} \text{Peak displacement} \\ \text{Peak acceleration} \\ \text{Max. drift} \\ \text{Residual drift} \\ . \end{array}\right\}$$

Once the structural response $\{R\}$ is obtained, we can determine the damage of members $\{D_M\}$ as

$$\{D_M\} = [M_{DMR}]\{R\}$$

Structural response vector

Member damage matrix

Member damage vector

For example,

$$\{D_M\} = \begin{Bmatrix} \text{Max. section force of the members} \\ \text{Member uctility factor} \\ \text{Residual drift of members} \\ . \end{Bmatrix}$$

We can know the damage degree of the structure from the damage of members as

$$\{D_S\} = [M_{DSM}]\{D_M\}$$

Member damage vector

Structural damage matrix

Structural damage vector

For example,

$$\{D_S\} = \left\{ \begin{matrix} \text{System ductility factor} \\ \text{System drift} \\ . \end{matrix} \right\}$$

Based on the structural damage degree vector $\{D_S\}$,
we can estimate the performance of the structure $\{\tilde{P}\}$
as

$$\{\tilde{P}\} = [M_{PDS}]\{D_S\}$$

Structural damage vector ($\{D_S\}$)

Performance evaluation matrix ($[M_{PDS}]$)

Vector of the performance which the structure has ($\{\tilde{P}\}$)

For example,

$$\{\tilde{P}\} = \begin{Bmatrix} \text{Down time} \\ \text{Repariung cost} \\ \text{Restriction to traffic} \\ . \end{Bmatrix}$$

Substituting

$$\{R\} = [M_{RG}]\{G\}$$

$$\{D_M\} = [M_{DMR}]\{R\}$$

$$\{D_S\} = [M_{DSM}]\{D_M\}$$

into

$$\{\tilde{P}\} = [M_{PDS}]\{D_S\}$$

We obtain

$$\{\tilde{P}\} = [\tilde{M}_{PG}]\{G\}$$

where

$$[\tilde{M}_{PG}] = [M_{PDS}][M_{DSM}][M_{DMR}][M_{RG}]$$

What are needed in the PBSD?

$$\{R\} = [M_{RG}]\{G\}$$

$$\{D_M\} = [M_{DMR}]\{R\}$$

$$\{D_S\} = [M_{DSM}]\{D_M\}$$

$$\{\tilde{P}\} = [M_{PDS}]\{D_S\}$$

Certain accumulation on the technical methods and experience

More technical developments are needed

Probabilistic Expression of the PSD (ATC-58)

$$E(DV) = \iiiint p(DV|DM)\,p(DM|EDP)\,p(EDP|IM)\,p(IM)$$

$E[DV]$: Expected loss or values

IM : Intensity of ground motion

$p(IM)$: probability of experiencing a given level of intensity

$p(EDP|IM)$: conditional probability of experiencing a level of response, given a level of ground motion intensity

$$E(DV) = \iiiint p(DV \mid DM)\, p(DM \mid EDP)\, p(EDP \mid IM)\, p(IM)$$

$p(DM \mid EDP)$: conditional probability of experiencing the damage state, given a level of structural response

$p(DV \mid DM)$: conditional probability of experiencing a loss of certain size, given a level of damage

What is the performance required from the Public?

Seismic Performance Goals

- Small to moderate earthquake

  Bridges should remain within the elastic range of the structural components without significant damage

- Large earthquake

  Bridges suffer damage but no collapse

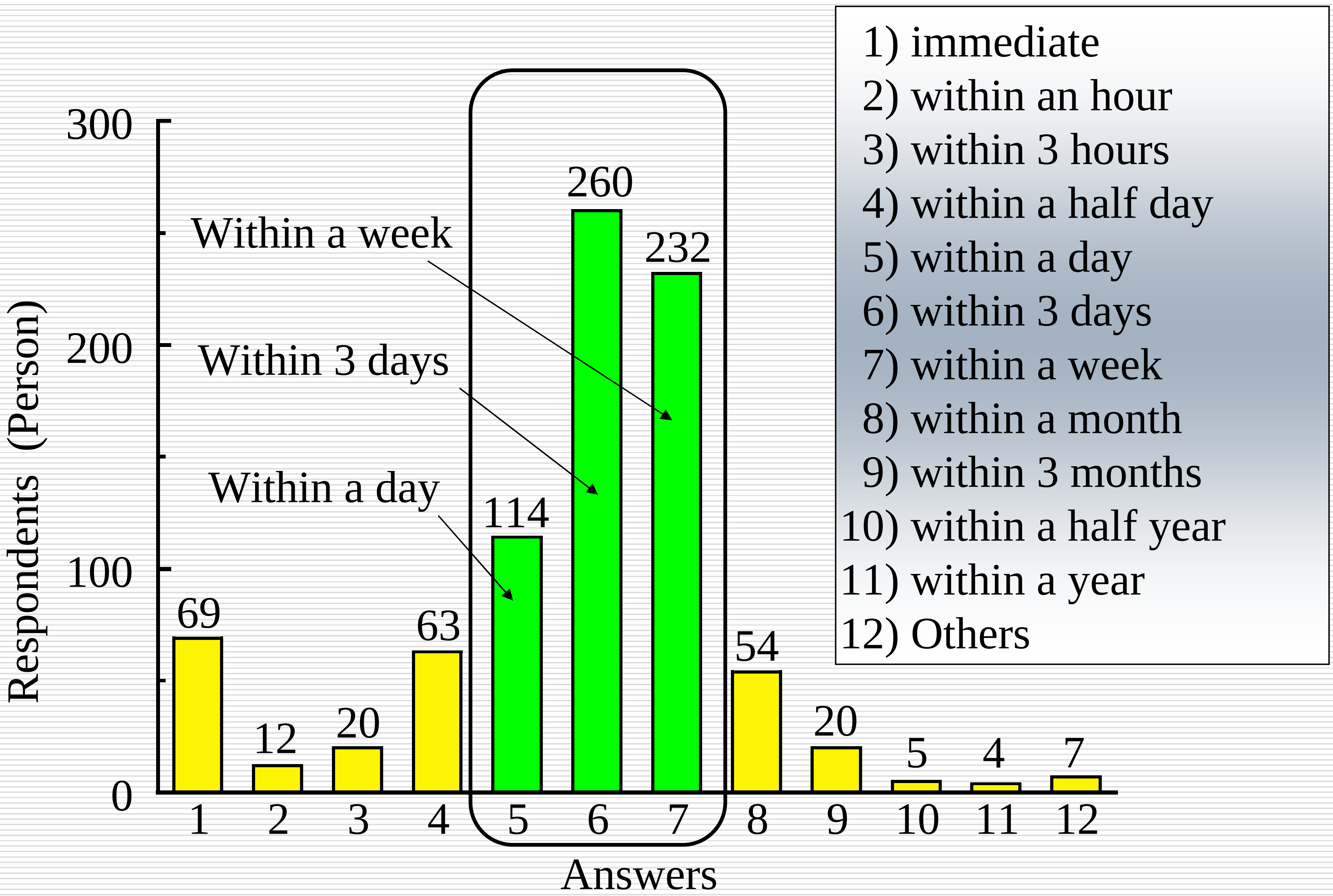
Questions to the Current Seismic Performance Goals?

- Can we accept extensive damage during a large earthquake, because we need bridges in such a disaster?
- How long downtime can the public accept?
- Enhancing the seismic performance needs more money, but how much cost increase is needed for it, and can the public accept it?
- Does the public recognize the current seismic performance goals, and do they appreciate them?

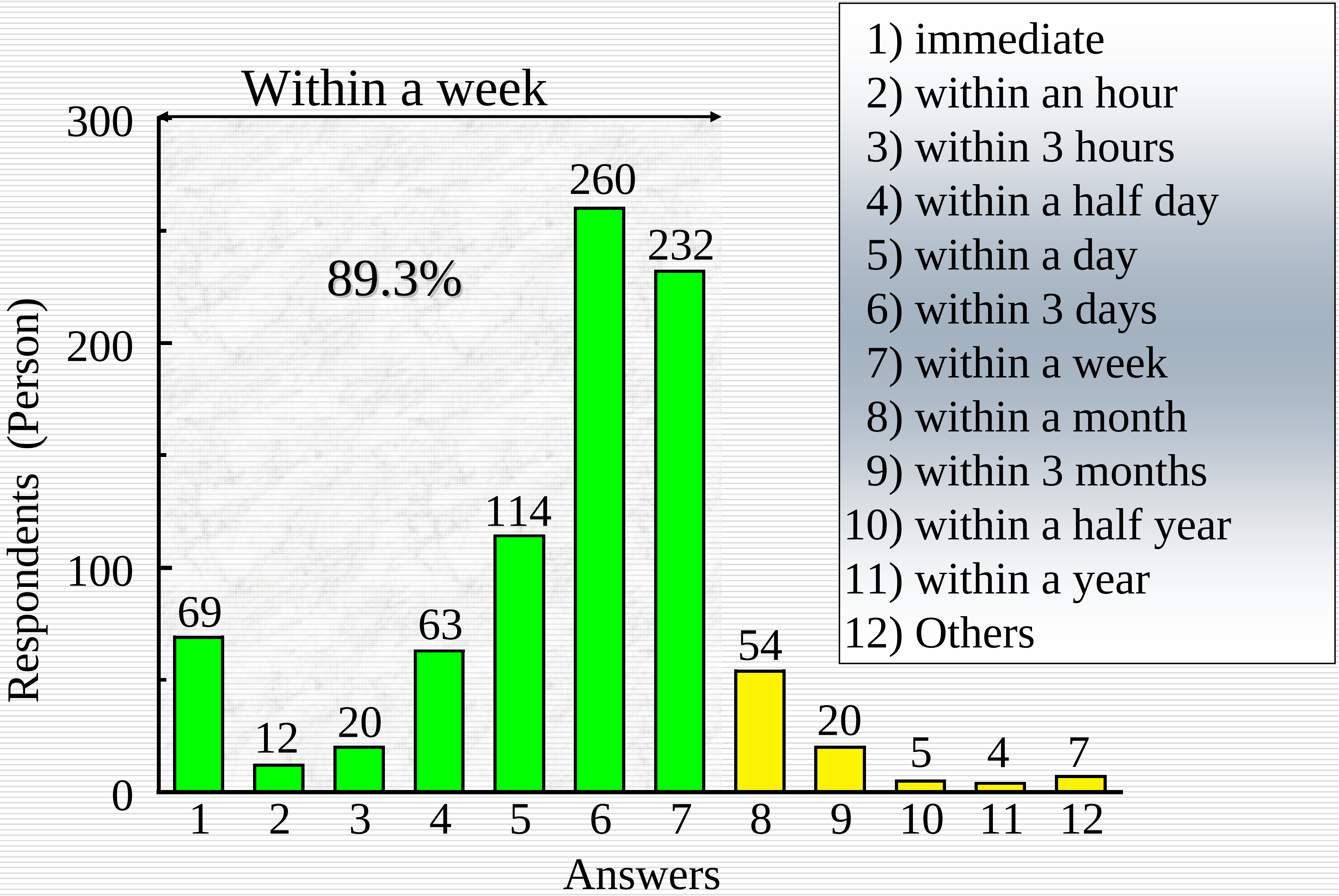
Questionnaire Survey to the Public on their Acceptance to the Damage of Bridges

- Asked the public on streets and shops in Tokyo
- Asked the public by sending questionnaire sheet by mail & e-mail
- Collected answers from 862 citizens with age of 10-80 at various zones in Japan
- Questions were given to
  - ✓Accepted downtime
  - ✓Accepted cost increase to build safer and more reliable bridges (“damage-free bridges”)
  - ✓Acceptance to the current seismic performance goals

Accepted Downtime



Accepted Downtime



Can we repair damaged bridges in a week?

● Repair period was investigated for 15 bridges which suffered damage in the 1995 Kobe, Japan earthquake

- ✓ Mukogawa bridge
- ✓ Juso bridge
- ✓ Hamate bridge
- ✓ …..

Mukogawa bridge

431m long 11-span bridge

- Spalling of cover concrete and local buckling of steel bars at columns
- Deck was dislocated laterally by 80cm due to the damage of bearings

Repair of Mukogawa bridge

	January	February	March	April
Preparation work	January 17	A half month		
Construct access road			A half month	
Repair substructures				1.8 months
Repair superstructure				2 months
Verification & inspection				
Restart of operation				April 17

Accepted downtime

▼ Accepted downtime by public

→ Within a week by 89.3% citizens

▼ In reality, in Kobe earthquake…

→ More than one month

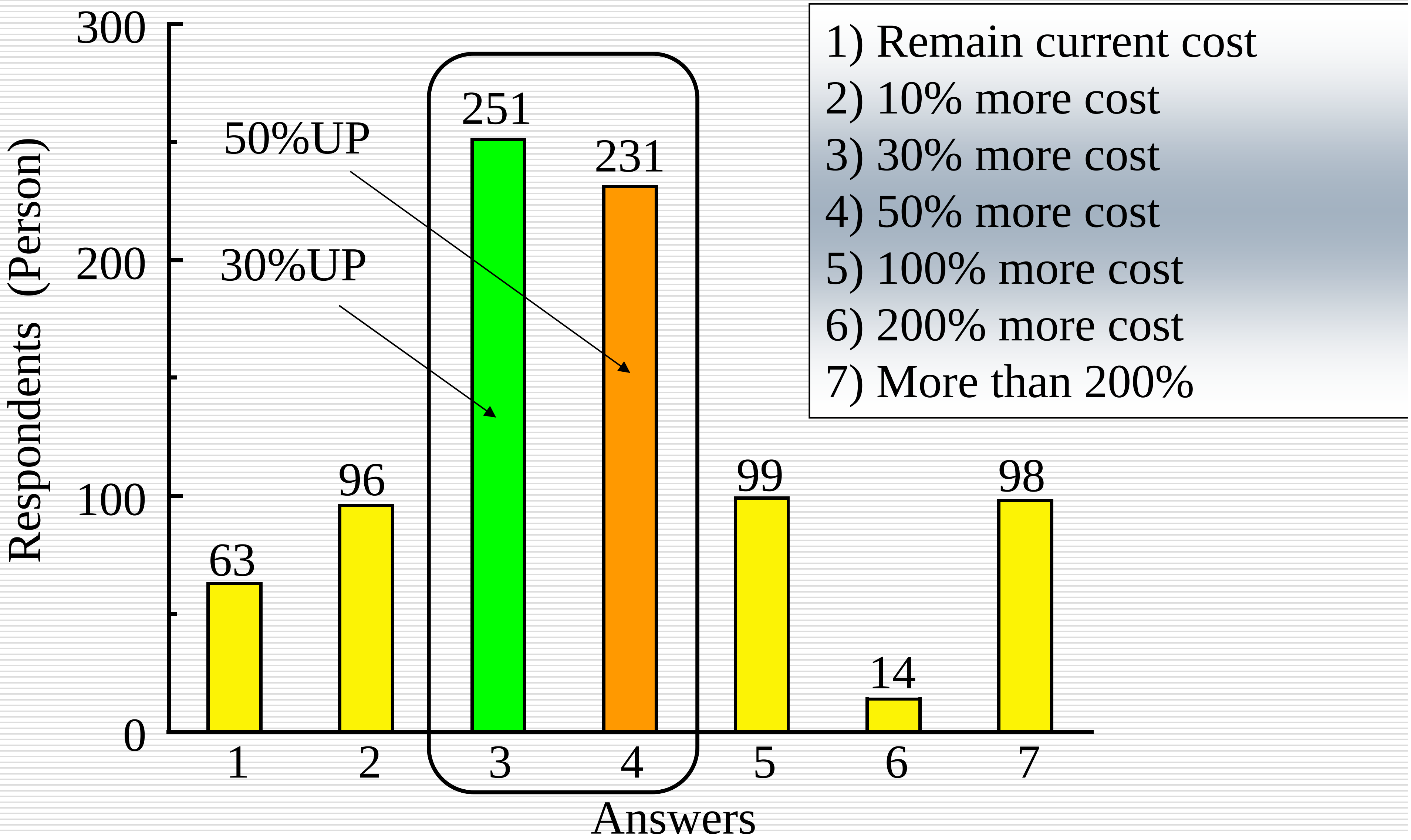
Is it impossible to build “damage free bridges”?

- No, it is possible, but it is not easy from 2 reasons
  - ✓Technical difficulty
  - ✓Economical constrain
- If the economical constrain is eliminated, it is possible to build “damage free bridges” based on even the current technology, except special bridges and conditions such as
  - ✓Bridges with special type & configuration
  - ✓Extensive soil failure

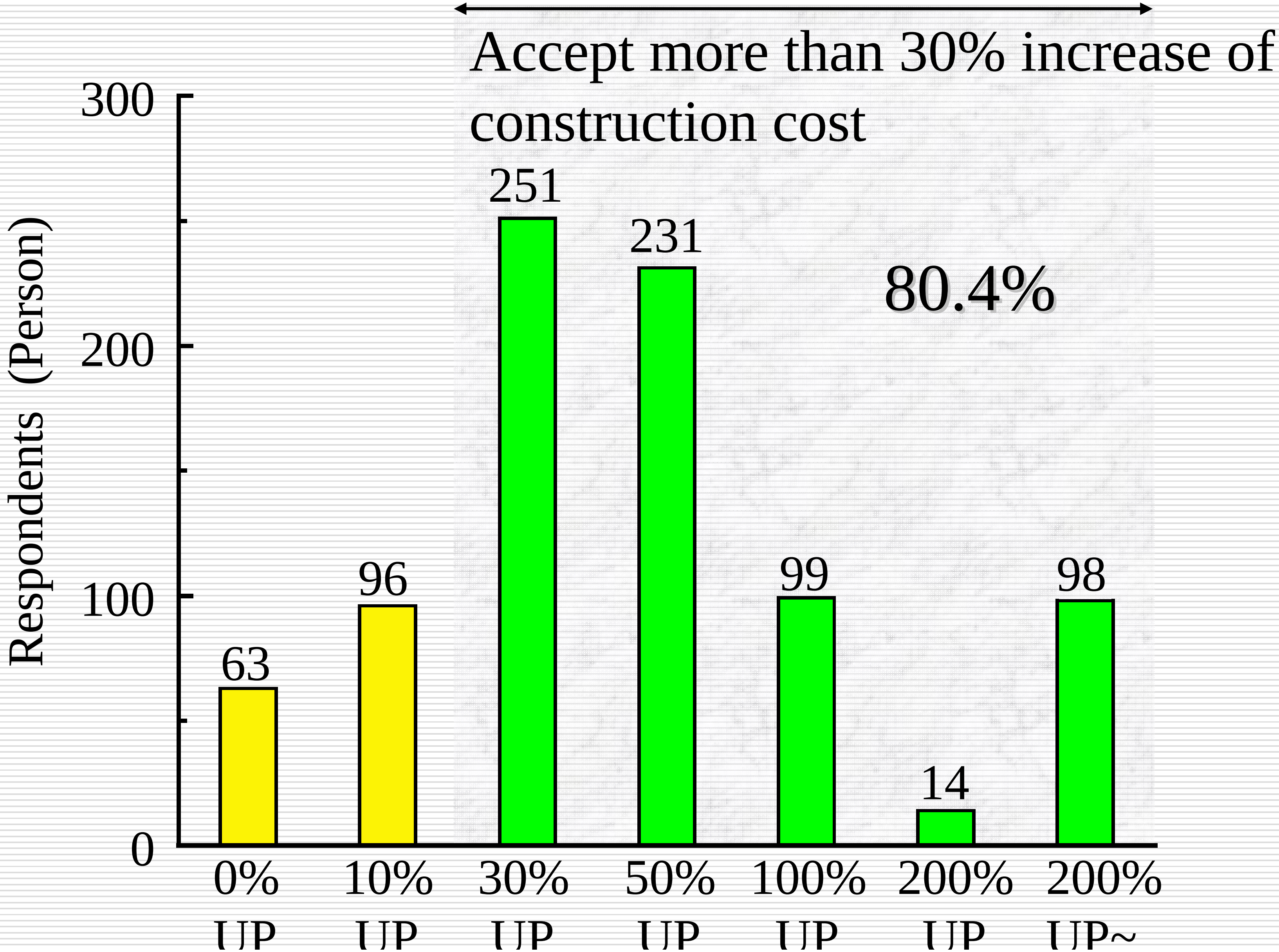
For ordinary bridges, what is the feasibility of building “damage free bridges”?

- How much cost increase can be accepted by the public?
- How much cost increase is required in construction?

How much cost increase can be accepted by the public for building “damage free bridges”?



How much cost increase can be accepted by the public for building "damage free bridges"?

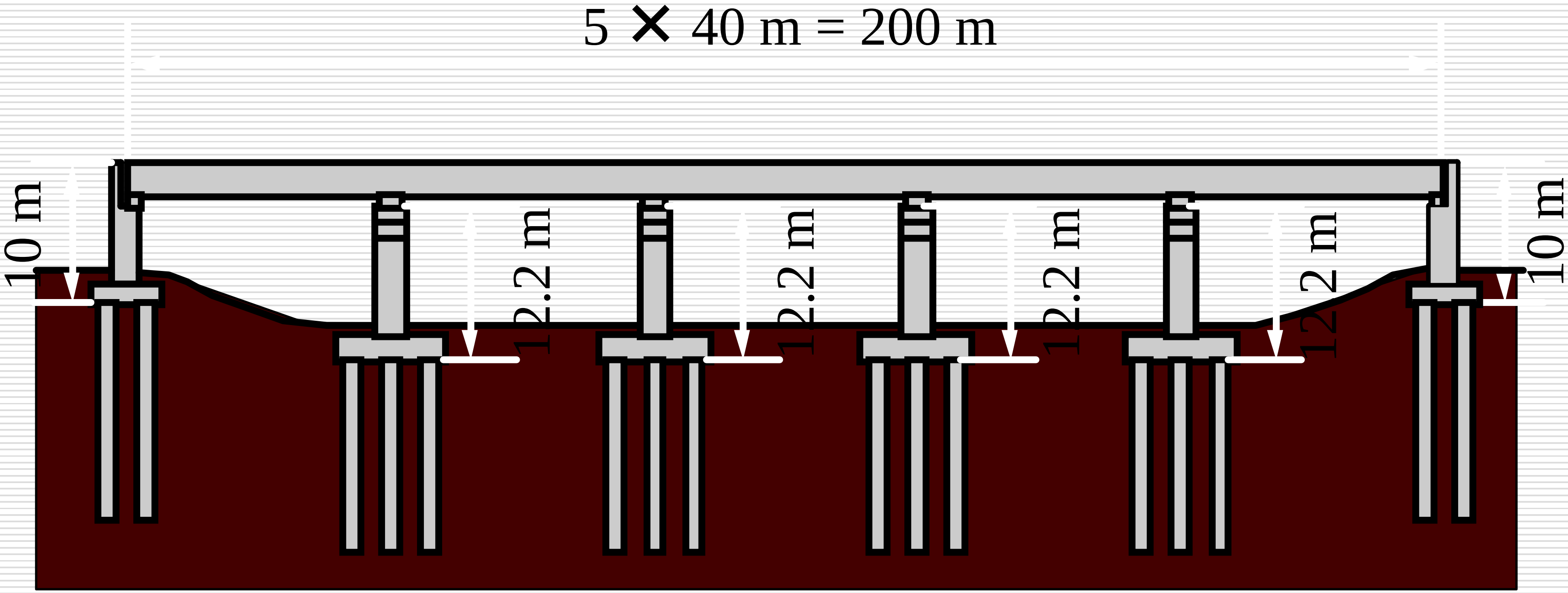


How much cost increase is required for construction of “damage free bridges”?

- Design a bridge assuming sufficiently high seismic force
- Assume that the current design criteria can be extended to design with higher than the current seismic force
- Evaluate cost of the bridge based on a standard cost estimate procedure

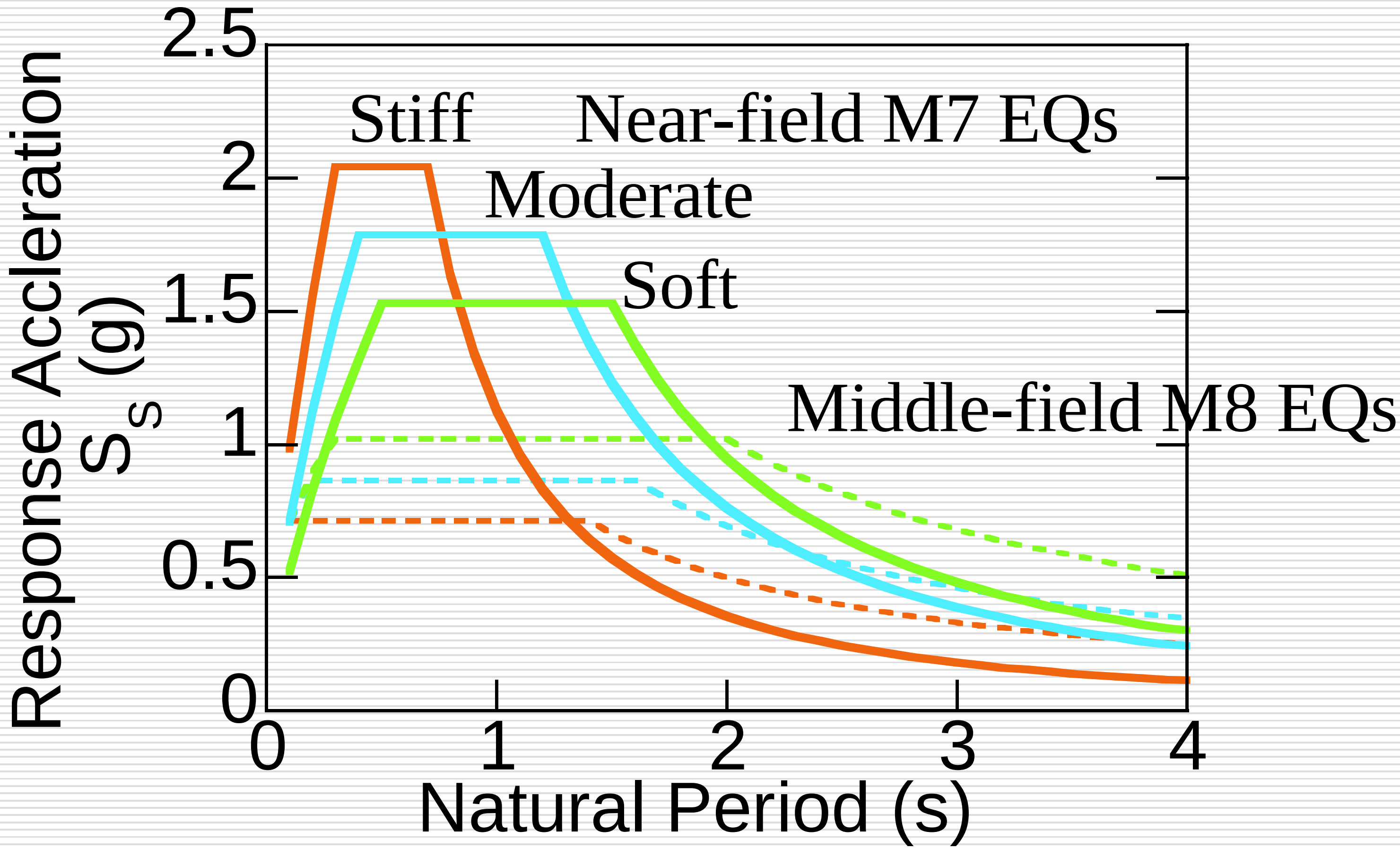
Target Bridge

A typical 5-span viaduct designed by Japan Design Specifications



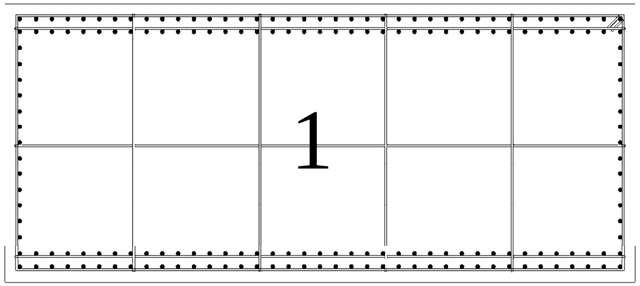
Near-Field Ground Accelerations

Safety Evaluation Ground Motions
Japan Road association (1997 & 2002)

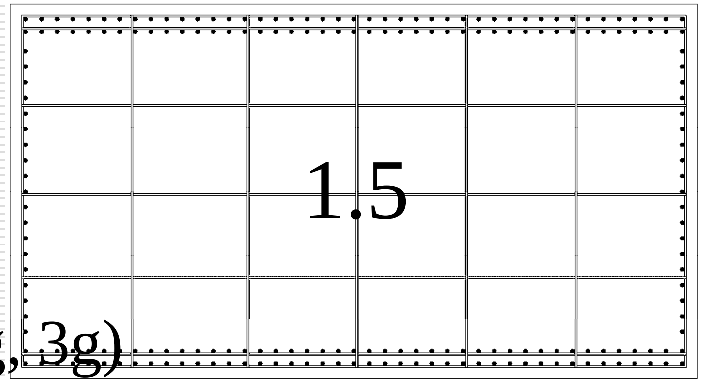


Effect of Design Seismic Force on the Column Section

1.75 g 5.0×2.2m



3 g 5.5×3.0m

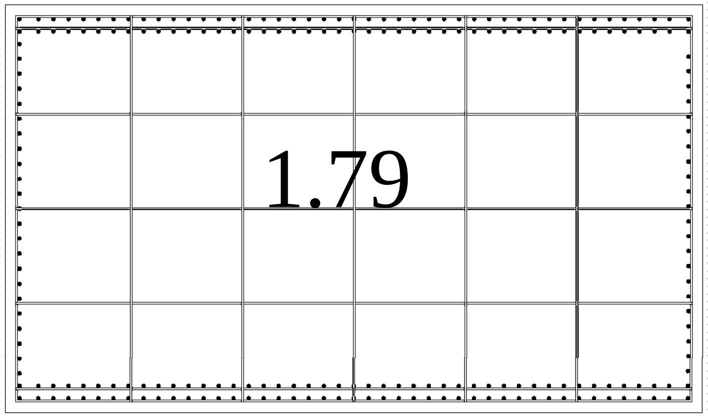


Tie bar : D16 at 150 mm interval (1.75g, 3g)

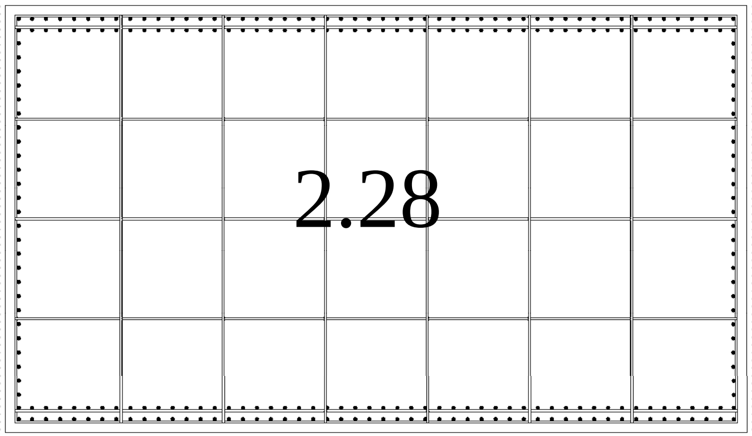
D19 at 150 mm interval (4g, 5g)

Longitudinal bars : D32 at every 125 mm interval

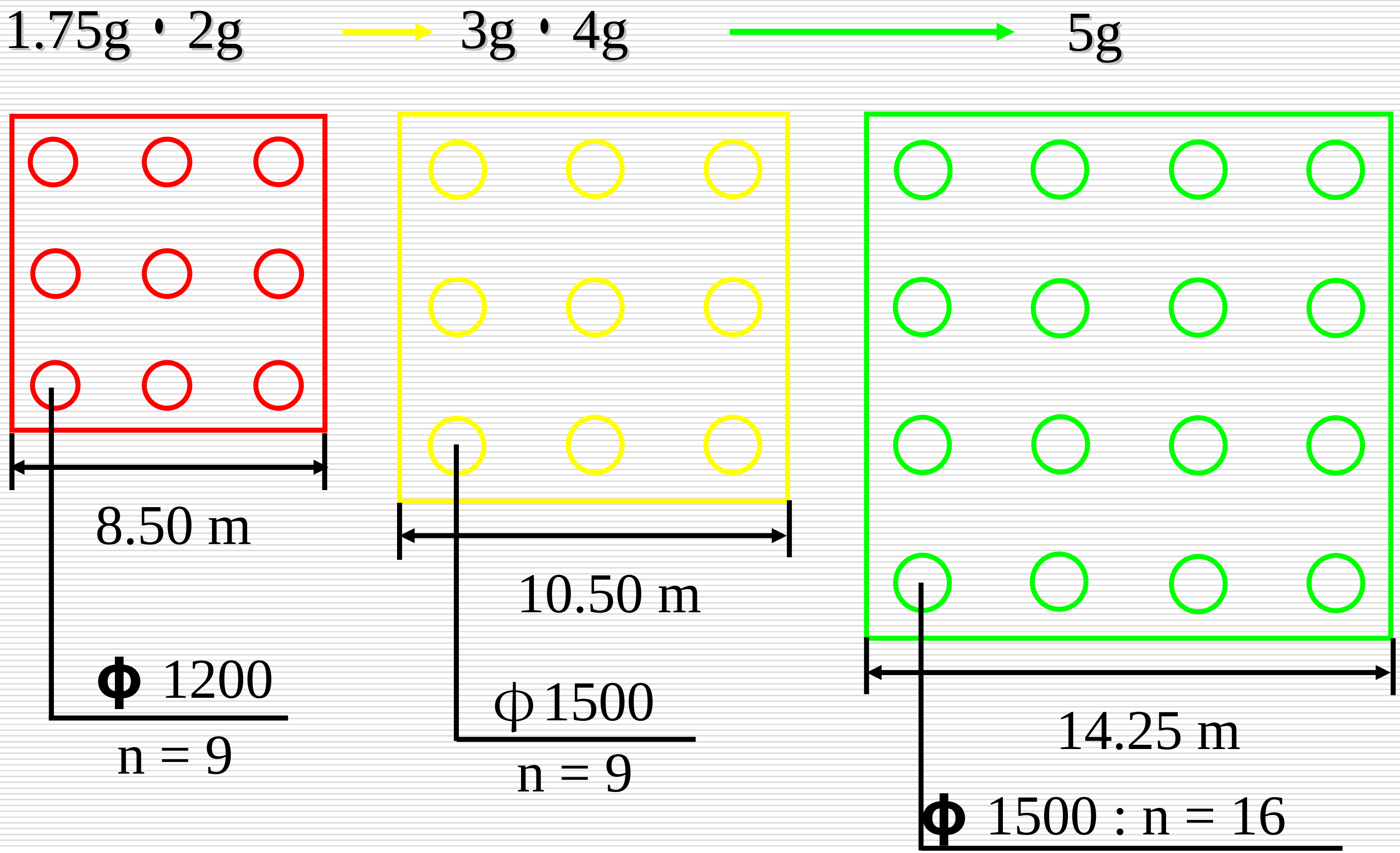
4 g 5.8×3.4m



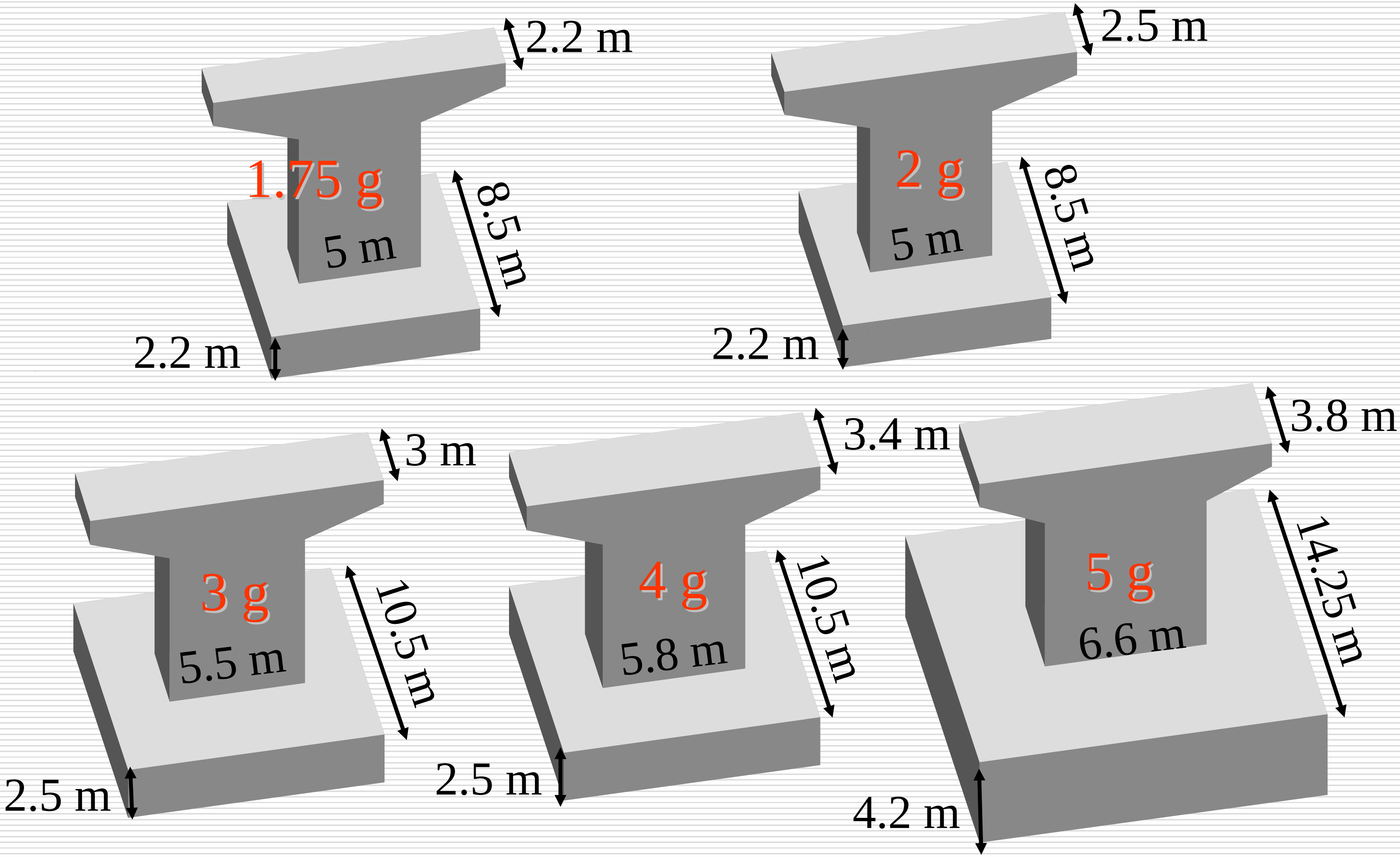
5 g 6.6×3.8m



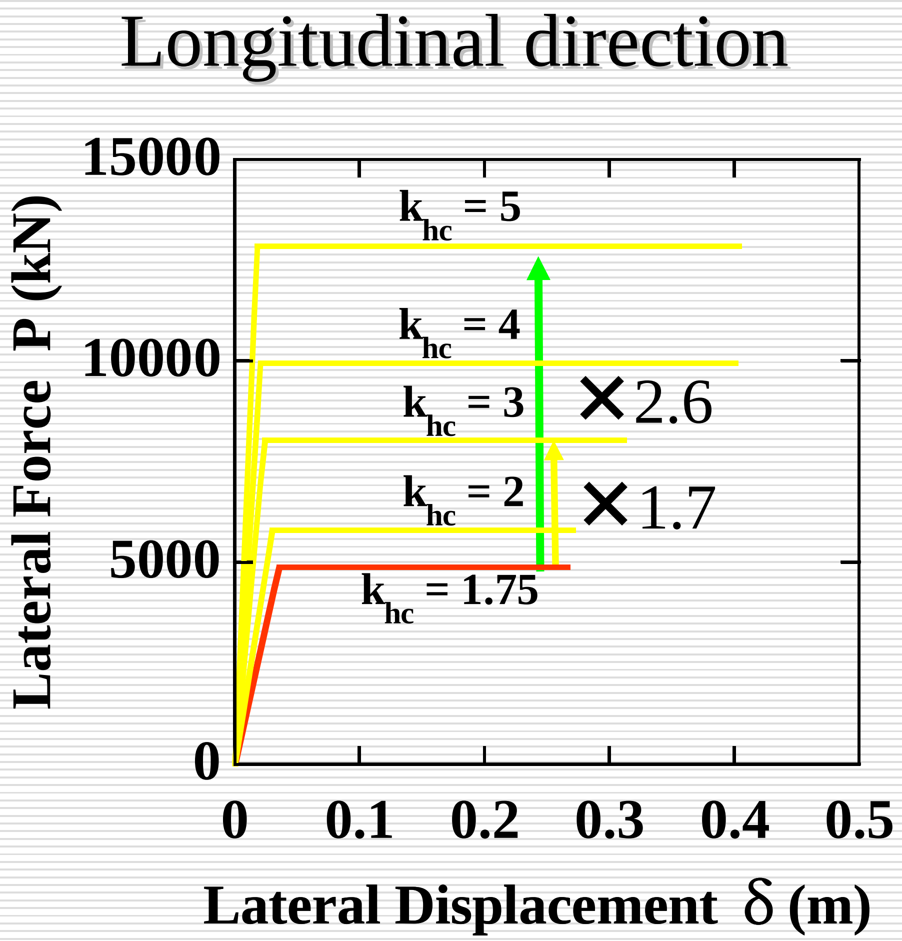
Effect of Design Seismic Force on the Footing and Pile Size



Effect of Design Seismic Force on the Column Size



How is the lateral capacity of the bridges enhanced depending on the lateral force coefficient?



Evaluation of Cost Increase

$$C(S) = C_D + C_S(S)$$

Design spectrum

Cost of substructure

Cost of superstructure

Cost of a bridge

Cost increase ratio

Substructure

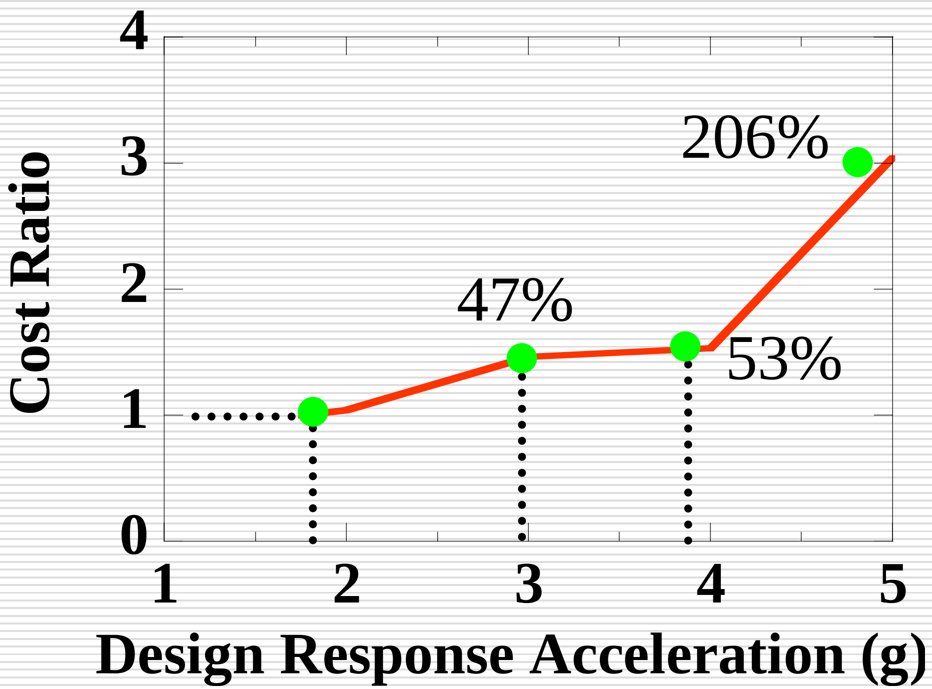
$$\alpha \equiv \frac{C_S(S)}{C_S(S = 1.75g)}$$

Superstructure

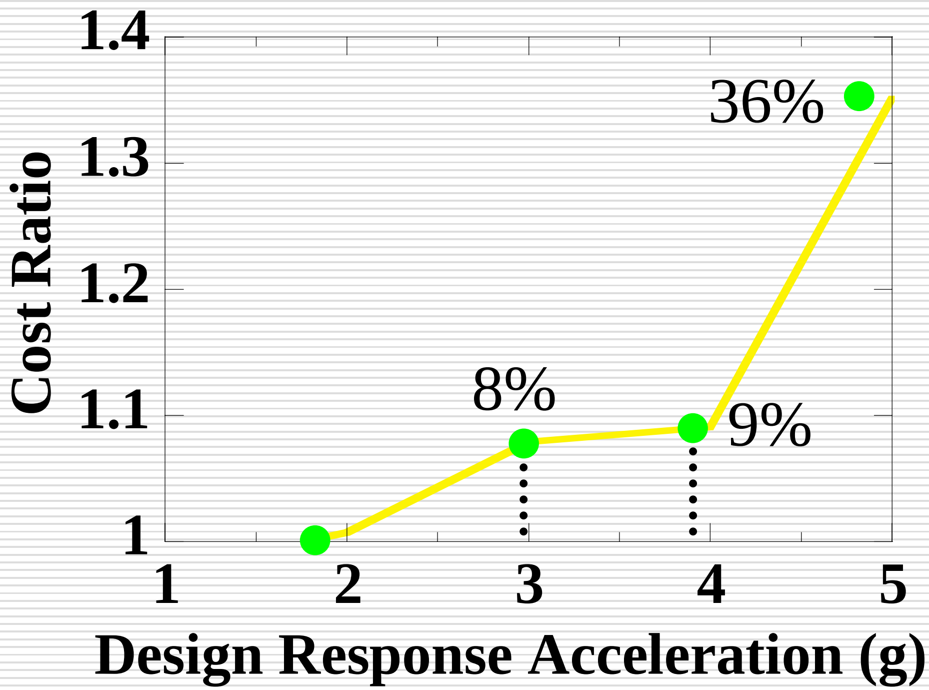
$$\alpha \equiv \frac{C(S)}{C(S = 1.75g)}$$

Effect of Design Seismic Force on the Cost Increase Ratio

Substructure



Total bridge= Superstructure+ Substructure



Conclusions

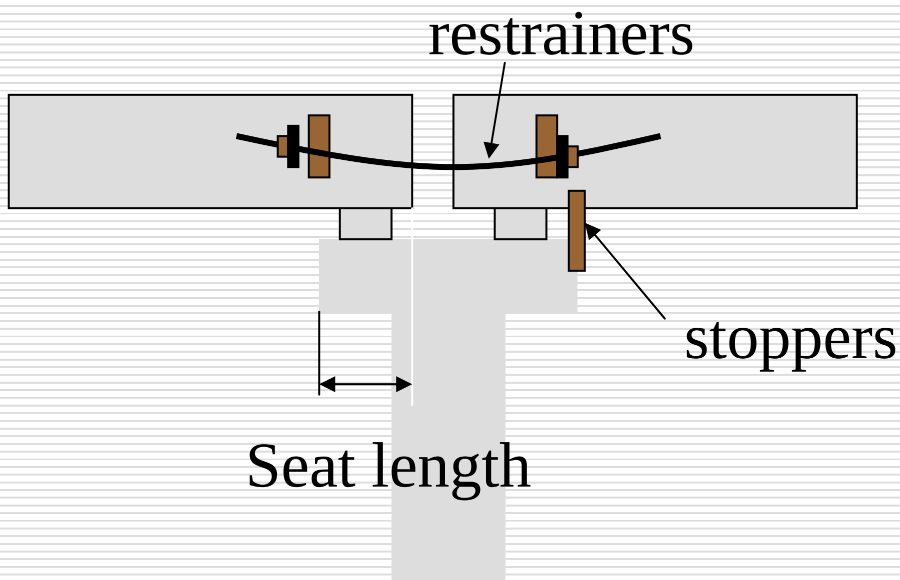
- 89.3% public demand that bridges should be repaired shorter than a week.
- However real downtime of bridges which suffered damage is far longer than accepted by the public.
- For building damage-free bridges which can maintain function during a significant earthquake, 80.4% public replied that cost increase can be validated if it is less than 30% of the current level.
- Cost increase required to build a damage free bridge is limited until the design response acceleration reaches 3g.

Design of Unseating Prevention Devices

Design of Unseating Prevention Devices

Types

- Stoppers
- Restrainers
- Seat Length

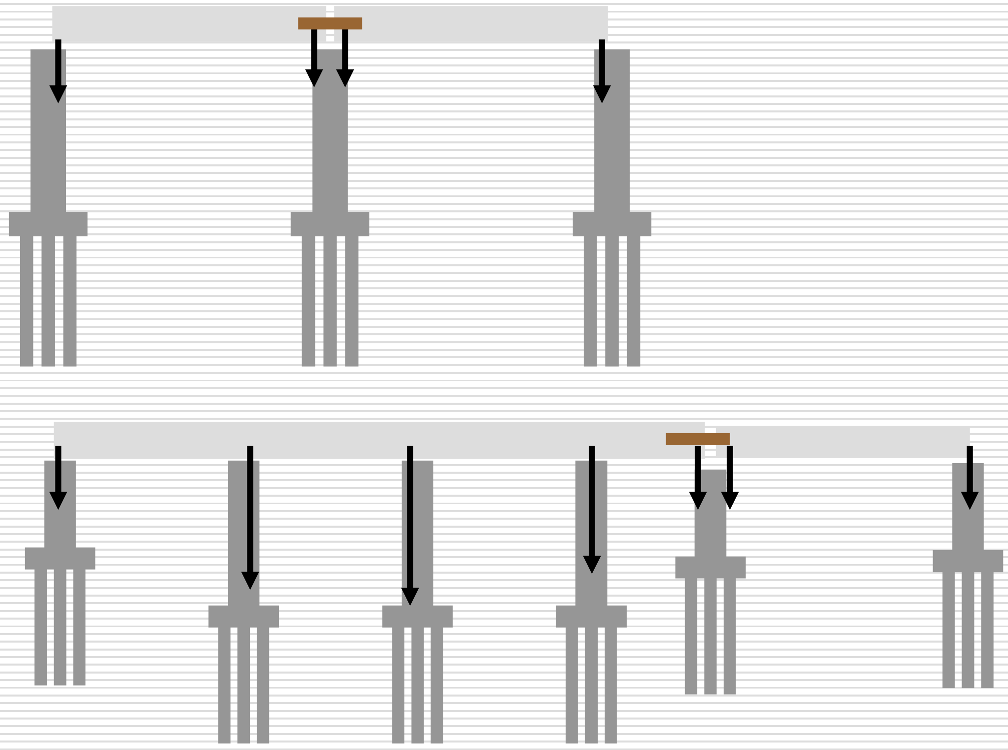


Design requirements

- Design force
- Design displacement for seat length

Design Force of Stoppers and Restrainers

$$F = \alpha \cdot k_h \cdot R$$



Seat Length

$$S_E = u_R + u_G > S_{EM}$$

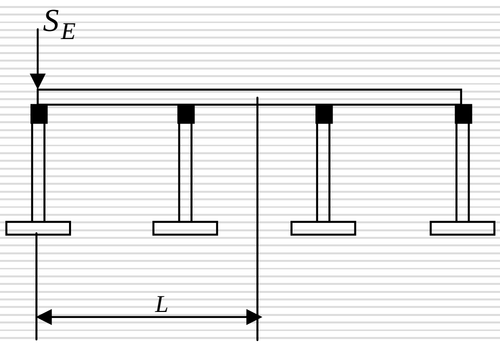
$$u_G = \varepsilon_G \cdot L$$

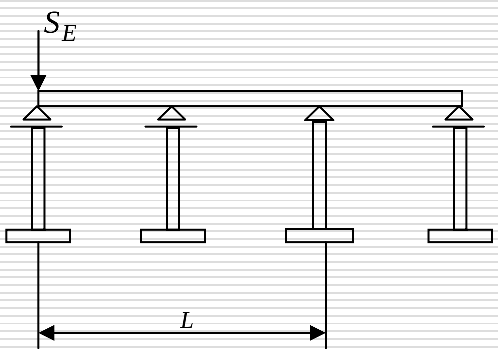
Ground strain along bridge axis

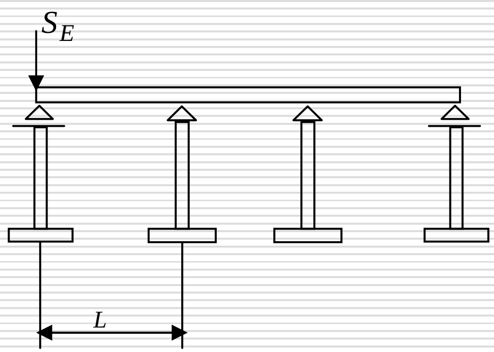
$$\varepsilon_G = \begin{cases} 0.0025 & \text{Type I} \\ 0.00375 & \text{Type II} \\ 0.005 & \text{Type III} \end{cases}$$

Which distance should we use for L?

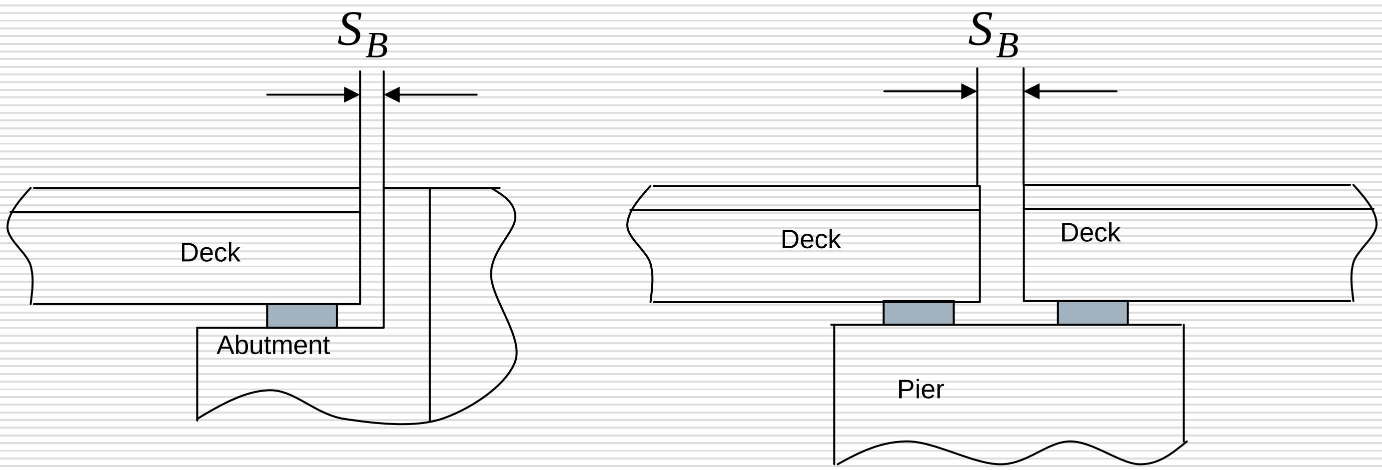
$$u_G = \varepsilon_G \cdot L$$







Distance between structures



New Restrainer Systems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