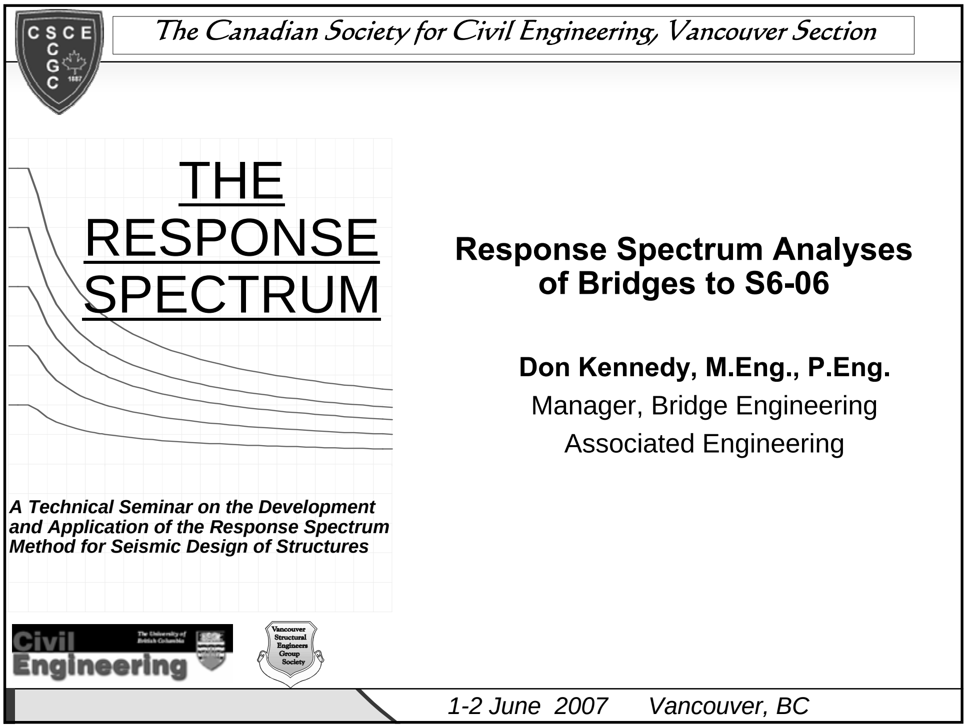


The Canadian Society for Civil Engineering, Vancouver Section

THE RESPONSE SPECTRUM

A Technical Seminar on the Development and Application of the Response Spectrum Method for Seismic Design of Structures

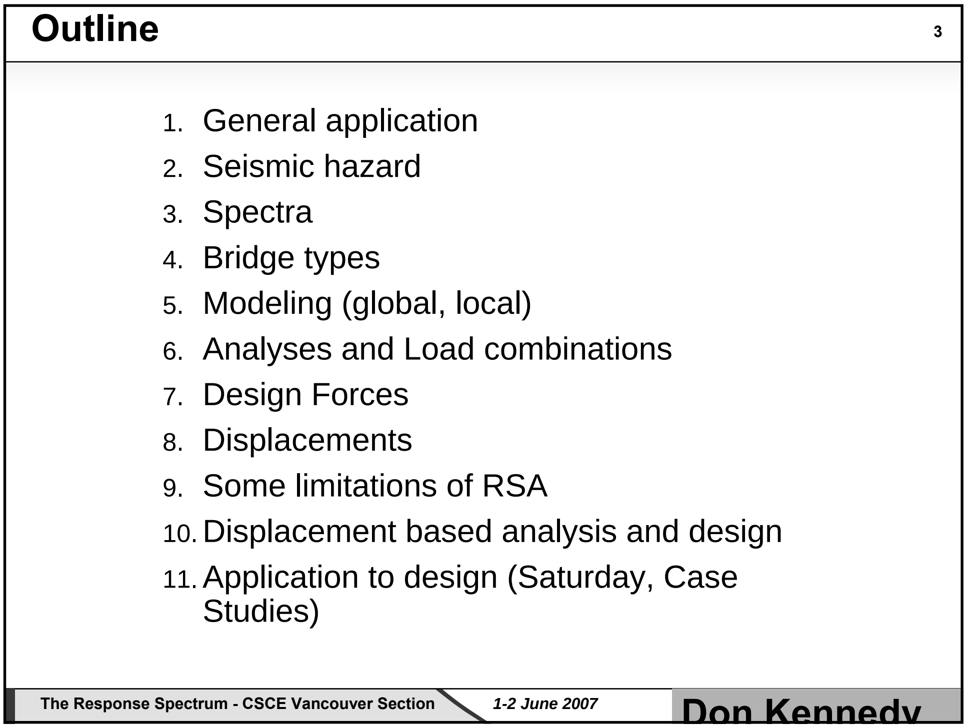
Response Spectrum Analyses of Bridges to S6-06

Don Kennedy, M.Eng., P.Eng.
Manager, Bridge Engineering
Associated Engineering

1-2 June 2007 Vancouver, BC

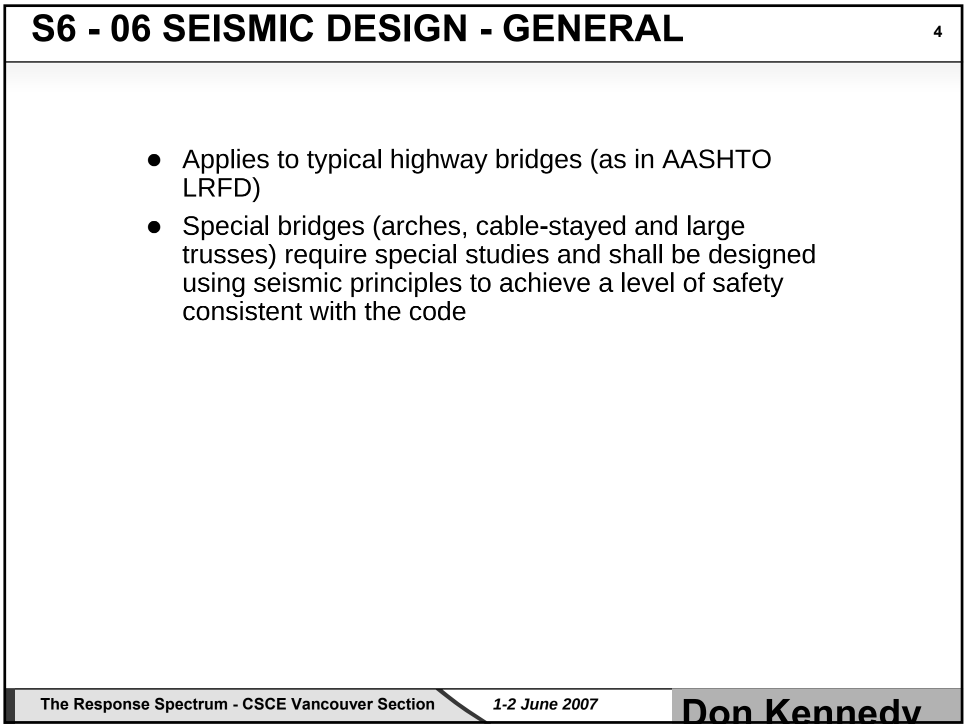
Acknowledgements

- Saqib Khan, Associated Engineering
- Sharlie Huffman, Ministry of Transportation
- Don Anderson (UBC); Denis Mitchell (McGill) Chair S6-06 Seismic Sub-committee



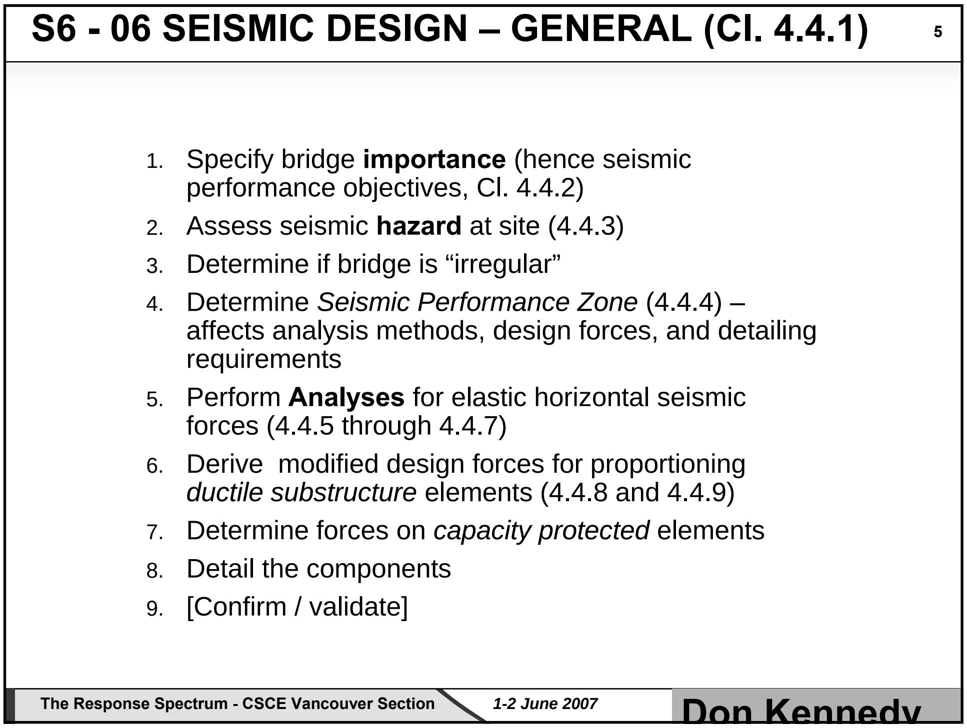
Outline

1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)



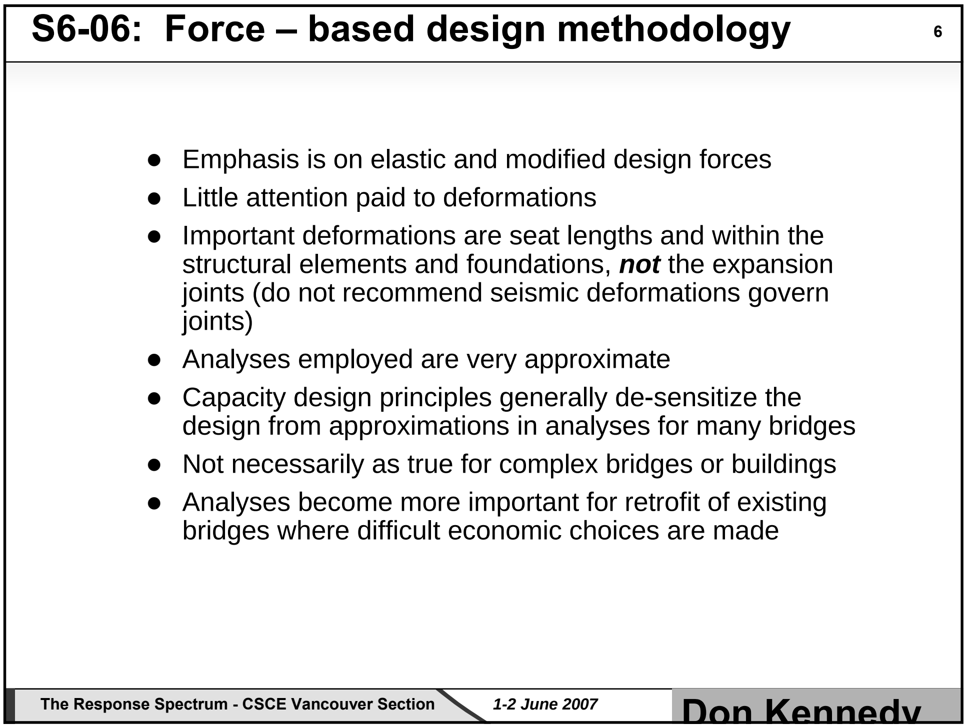
S6 - 06 SEISMIC DESIGN - GENERAL

- Applies to typical highway bridges (as in AASHTO LRFD)
- Special bridges (arches, cable-stayed and large trusses) require special studies and shall be designed using seismic principles to achieve a level of safety consistent with the code



S6 - 06 SEISMIC DESIGN – GENERAL (Cl. 4.4.1)

1. Specify bridge **importance** (hence seismic performance objectives, Cl. 4.4.2)
2. Assess seismic **hazard** at site (4.4.3)
3. Determine if bridge is “irregular”
4. Determine *Seismic Performance Zone* (4.4.4) – affects analysis methods, design forces, and detailing requirements
5. Perform **Analyses** for elastic horizontal seismic forces (4.4.5 through 4.4.7)
6. Derive modified design forces for proportioning *ductile substructure* elements (4.4.8 and 4.4.9)
7. Determine forces on *capacity protected* elements
8. Detail the components
9. [Confirm / validate]



S6-06: Force – based design methodology

- Emphasis is on elastic and modified design forces
- Little attention paid to deformations
- Important deformations are seat lengths and within the structural elements and foundations, ***not*** the expansion joints (do not recommend seismic deformations govern joints)
- Analyses employed are very approximate
- Capacity design principles generally de-sensitize the design from approximations in analyses for many bridges
- Not necessarily as true for complex bridges or buildings
- Analyses become more important for retrofit of existing bridges where difficult economic choices are made

Outline

1. General application
2. **Seismic hazard**
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)

Seismic hazard

- Zonal acceleration (A) shall be determined either Table A3.1.1, or
- from Table 4.1, using the PHA specified in Figure A3.1.6 or as provided by the Geological Survey of Canada *using the seismic hazard methodology used to generate Figure A3.1.6*
- MoT (British Columbia) Supplement to S6-00 requires the use of PHA as obtained from PGC in lieu of “A”

Seismic hazard; Table 4.1

		Seismic performance zone	
Range of PHA (g) for 10% probability of exceedance in 50 years (From Figure A3.1.6)	Zonal acceleration ratio, **A**	Lifeline bridges	Emergency-route and other bridges
0.00<PHA<0.04	0	2	1
0.04<=PHA<0.08	0.05	2	1
0.08<=PHA<0.11	0.1	3	2
0.11<=PHA<0.16	0.15	3	2
0.16<=PHA<0.23	0.2	3	3
0.23<=PHA < 0.32	0.3	4	4
0.32 or greater	0.4	4	4

Outline

1. General application
2. Seismic hazard
3. **Spectra**
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)

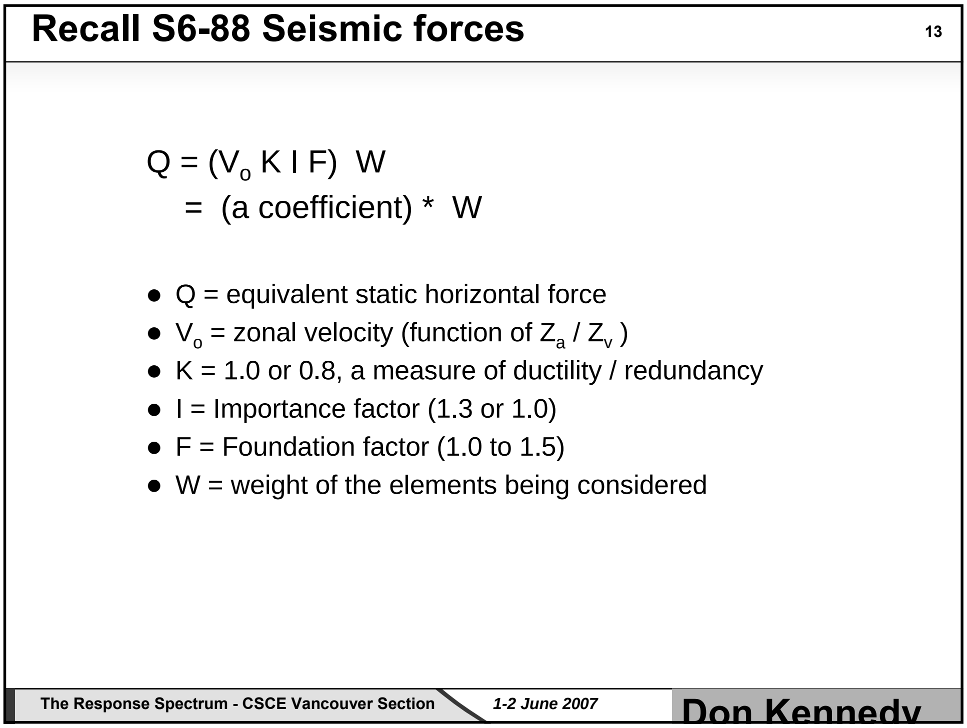
C_{sm} coefficient : Elastic response spectrum

$$C_{sm} = 1.2\,A\,I\,S\,/\,T_m^{2/3} \leq 2.5\,AI, \quad T_m < 4.0 \text{ sec}$$
$$= 3\,A\,I\,S\,/\,T_m^{4/3}, \quad T_m > 4 \text{ sec}$$

- C_{sm} = ordinate of design response spectrum
- T_m = period of vibration of mth mode, second
- A = zonal acceleration ratio, 10% prob'y of exc'c.
- I = Importance factor
- S = Soil coefficient

Site Specific Elastic Response Coefficient

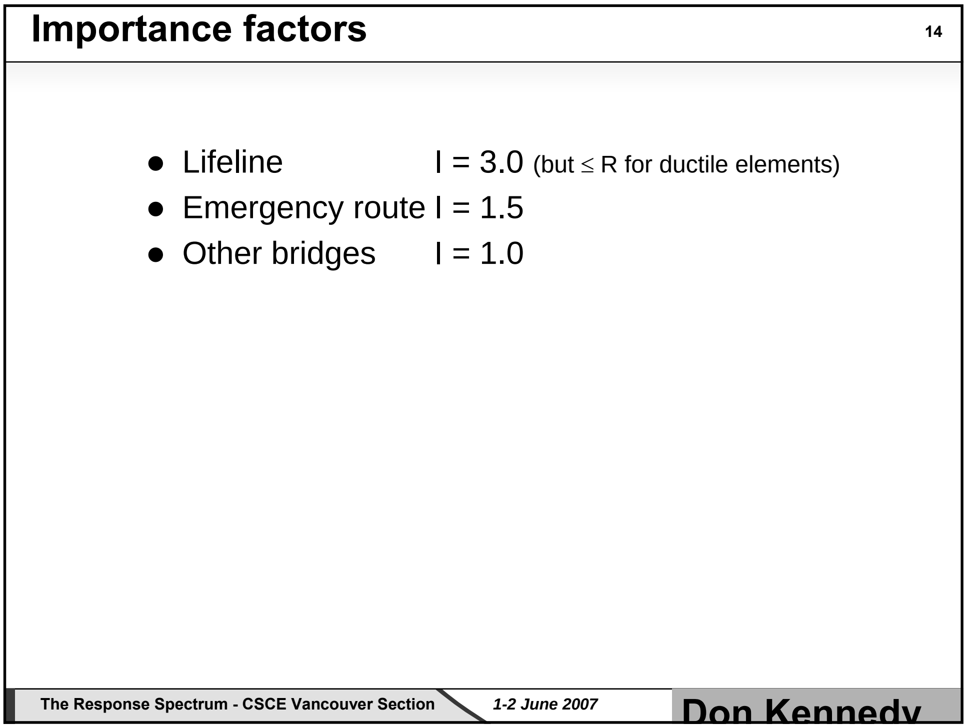
- Site specific response spectra may be used with approval of the Regulatory Authority
- Cl. 4.4.7.3: **Ordinates of site specific response spectra shall not be less than $0.8C_{sm}$**



Recall S6-88 Seismic forces

$$Q = (V_o\ K\ I\ F)\ W$$
$$= \text{(a coefficient)} * W$$

- Q = equivalent static horizontal force
- V_o = zonal velocity (function of Z_a / Z_v)
- K = 1.0 or 0.8, a measure of ductility / redundancy
- I = Importance factor (1.3 or 1.0)
- F = Foundation factor (1.0 to 1.5)
- W = weight of the elements being considered



Importance factors

- Lifeline I = 3.0 (but ≤ R for ductile elements)
- Emergency route I = 1.5
- Other bridges I = 1.0

“I” S6-06 & AASHTO, I = 3, multi-column bent

	CSA S6-00 or S6-06	AASHTO LRFD-94
Multi-column Bent	$C_{sm\ max}$ = 2.5 A **I** = 2.5(0.2)(**3.0) = 1.50**	$C_{sm\ max}$ = 2.5 A = 2.5(0.2) = 0.50
	R = 5.0	**R = 1.5** (Critical bridge)
	$C_{sm\ max}$ /R = 1.5/5.0 **= 0.30**	$C_{sm\ max}$ /R = 0.50/1.5 **= 0.33**

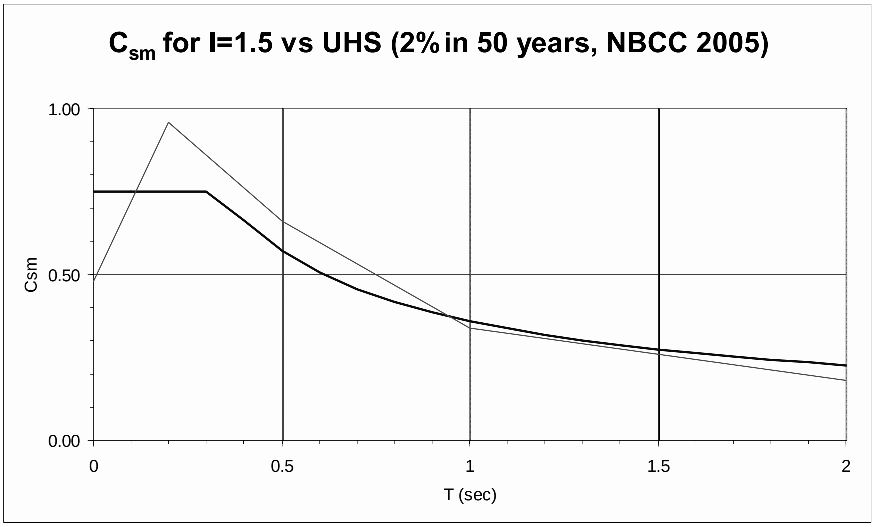
Importance factor “I” : S6-06 & AASHTO, I = 1.5

	CSA S6-00 or S6-06	AASHTO LRFD-94
Single column pier	$C_{sm\ max}$ = 2.5 A **I** = 2.5(0.2)(**1.5) = 0.75**	$C_{sm\ max}$ = 2.5 A = 2.5(0.2) = 0.50
	R = 3.0	R = 2.0 (Essential bridge)
	$C_{sm\ max}$ /R = 0.75/3.0 = **0.25**	$C_{sm\ max}$ /R = 0.50/2.0 = **0.25**
Abutment	$C_{sm\ max}$ = 2.5 AI = 2.5(0.2)(1.5) = 0.75	$C_{sm\ max}$ = 2.5 A = 2.5(0.2) = 0.50
	R = 1.0	R = 1.0
	$C_{sm\ max}$ /R = 0.75/1.0 **= 0.75**	$C_{sm\ max}$ /R = 0.50/1.0 **= 0.50**

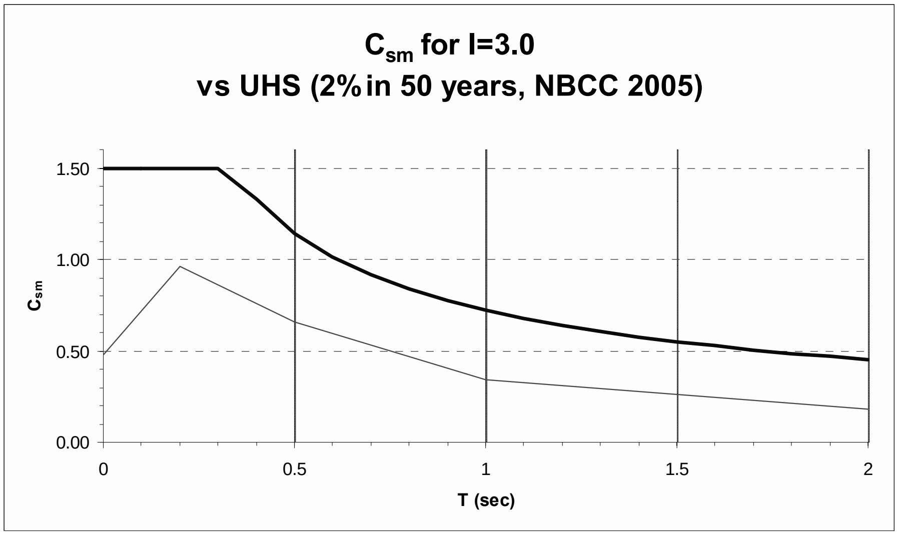
Importance factor: S6-06 & AASHTO, I = 3

	CSA S6-00 or S6-06	AASHTO LRFD-94
Single column Pier	$C_{sm\ max}$ = 2.5 A **I** = 2.5(0.2)(**3.0) = 1.50**	$C_{sm\ max}$ = 2.5 A = 2.5(0.2) = 0.50
	R = 3.0	R = 1.5 (Critical bridge)
	$C_{sm\ max}$ /R = 1.5/3.0 **= 0.50**	$C_{sm\ max}$ /R = 0.50/1.5 **= 0.33**
Abutment	$C_{sm\ max}$ = 2.5 AI = 2.5(0.2)(3.0) = 1.50	$C_{sm\ max}$ = 2.5 A = 2.5(0.2) = 0.50
	R = 1.0	**R = 1.0**
	$C_{sm\ max}$ /R = 1.50/1.0 **= 0.50**	$C_{sm\ max}$ /R = 0.50/1.0 **= 0.50**

C_{sm} Comparison to UHS and I factors (Vancouver)


C_{sm} for I=1.5 vs UHS (2% in 50 years, NBCC 2005)

C_{sm} Comparison to UHS and I factors (Vancouver)



C_{sm} for I=3.0
vs UHS (2% in 50 years, NBCC 2005)

Possible alternative approach to “I” factors

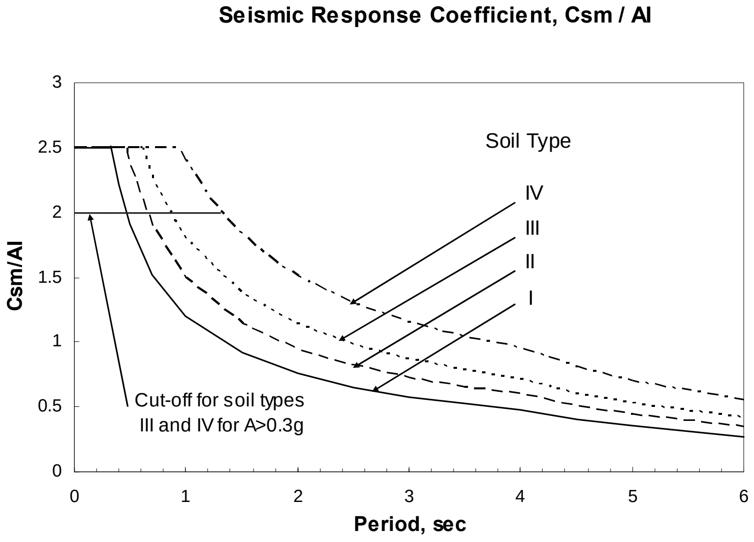
An Importance Factor (I) of 1.0 may be appropriate if:

- Site specific studies for 1000-year and 2500-year events.
- Bridge performance is demonstrated for the 1000-year event and for a “collapse prevention” limit state for a 2500-year event.
- Dynamic analyses are undertaken for both of the above events. Emphasis on deformations. Foundation and soil conditions accounted for.
- Component deformation capacities are determined for members expected to experience inelastic deformations.
- Deformation demands determined using non-linear static methods or NL time-history. Include foundation flexibility and significant non-linear soil effects on substructure seismic performance.
- Special bridges

Soil coefficient

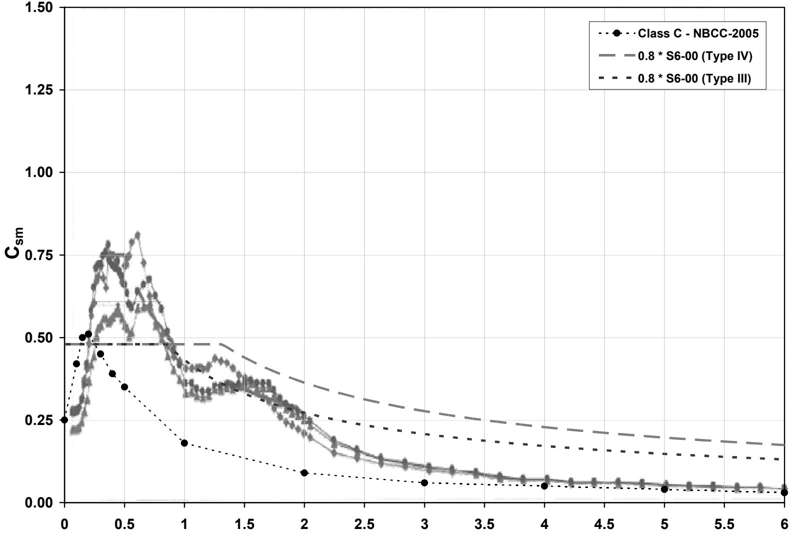
- S = 1.0, 1.25, 1.5 or 2.0, an amplification coefficient depending on the foundation conditions. The deeper and/or softer the soil the higher the coefficient.
- Weak soils in high hazard areas cannot transmit high accelerations, and so have a reduction for short period response.

Soil coefficient, effect on spectral shape



DESIGN RESPONSE SPECTRA

Computed 475-Year Acceleration Response Spectra at Surface
5% Damping I=1.0



Outline

1. General application
2. Seismic hazard
3. Spectra
4. **Bridge types**
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)

Bridge types

1. Regular?
2. Irregular?
3. Reference to clause 4.4.5.3.2 and corresponding table
4. Intention is based on AASHTO, such that comparison of analyses match more rigorous analyses in most cases
5. Affects type of analyses
6. Multi-mode RSA not too onerous even for regular bridges
7. Hand calculation checks give good agreement for regular bridges

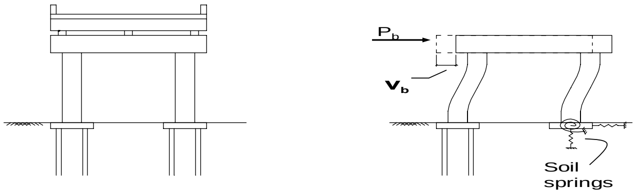
Bridge Seismic Performance (Commentary C4.4.2)

	Lifeline	Emergency-route	Other
Small to moderate earthquake	All traffic Immediate use	All traffic Immediate use	All traffic Immediate use
Design earthquake (475 year return period)	All traffic Immediate use	Emergency vehicles Immediate use	Repairable damage
Large earthquake (e.g. 1000 year return period)	Emergency vehicles Immediate use	Repairable damage	No collapse

Outline

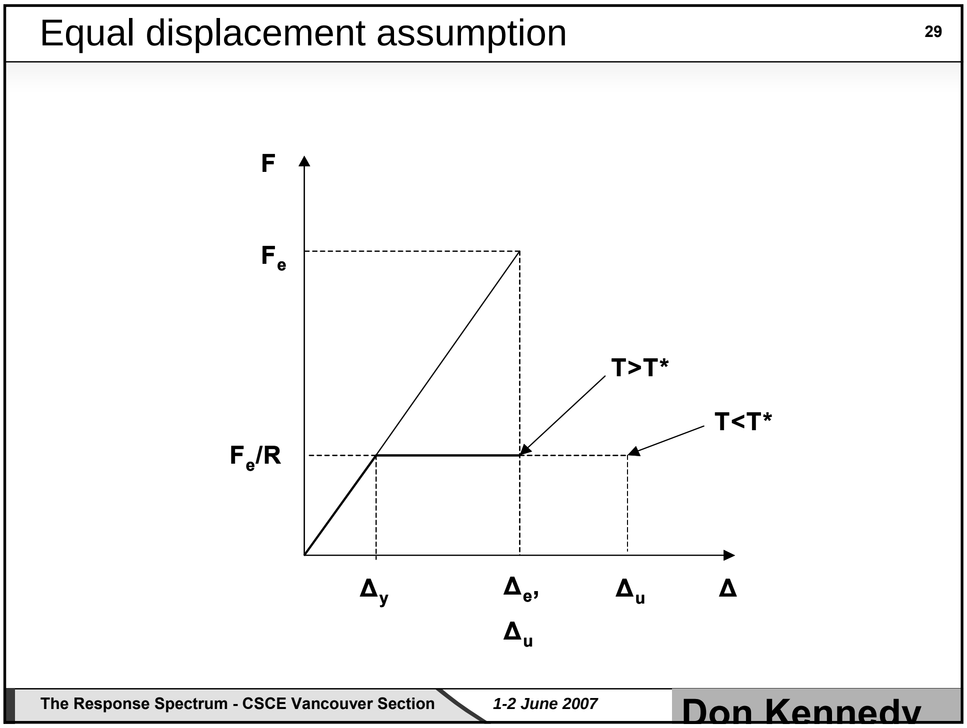
1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. **Modeling (global, local) (Discuss Saturday)**
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)

Concrete pier stiffness

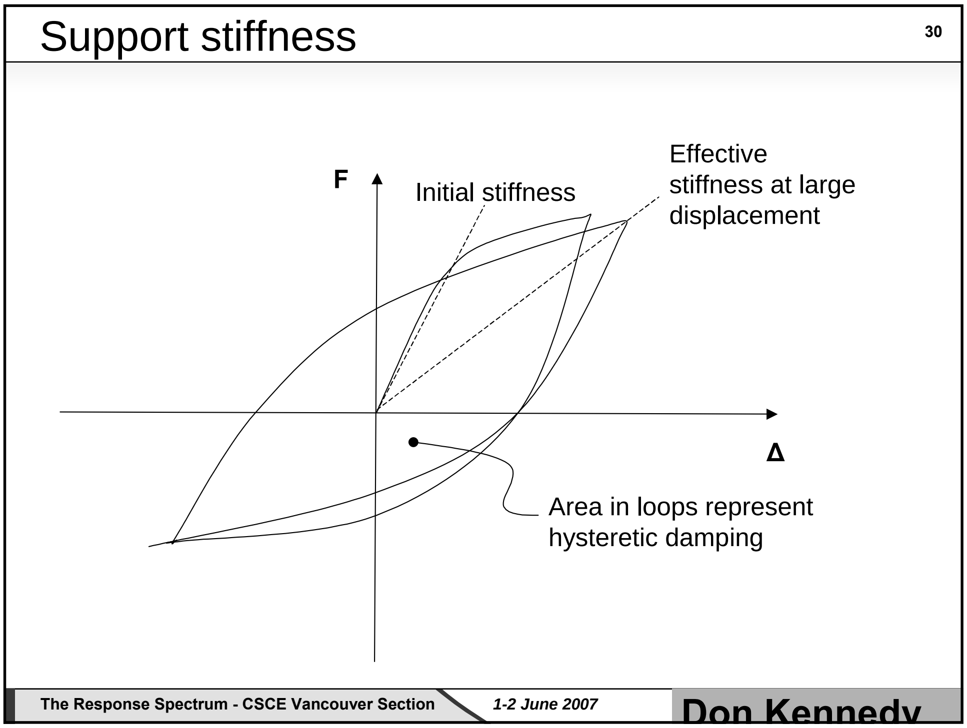


Clause 4.5.1:

May use $EI_{cracked}$ or EI_{gross} in determining K for forces
Shall use $EI_{cracked}$ for K for displacements
Should use $EI_{cracked}$ for K for all analyses
I suggest that foundation flexibility be included if piled



Equal displacement assumption

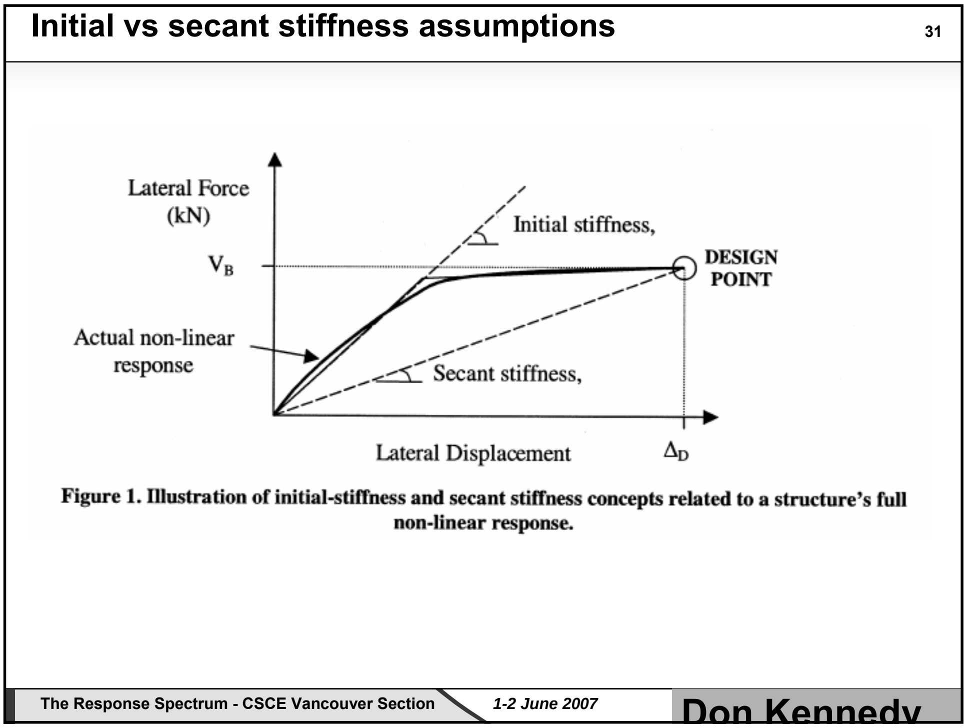


Support stiffness

Initial stiffness

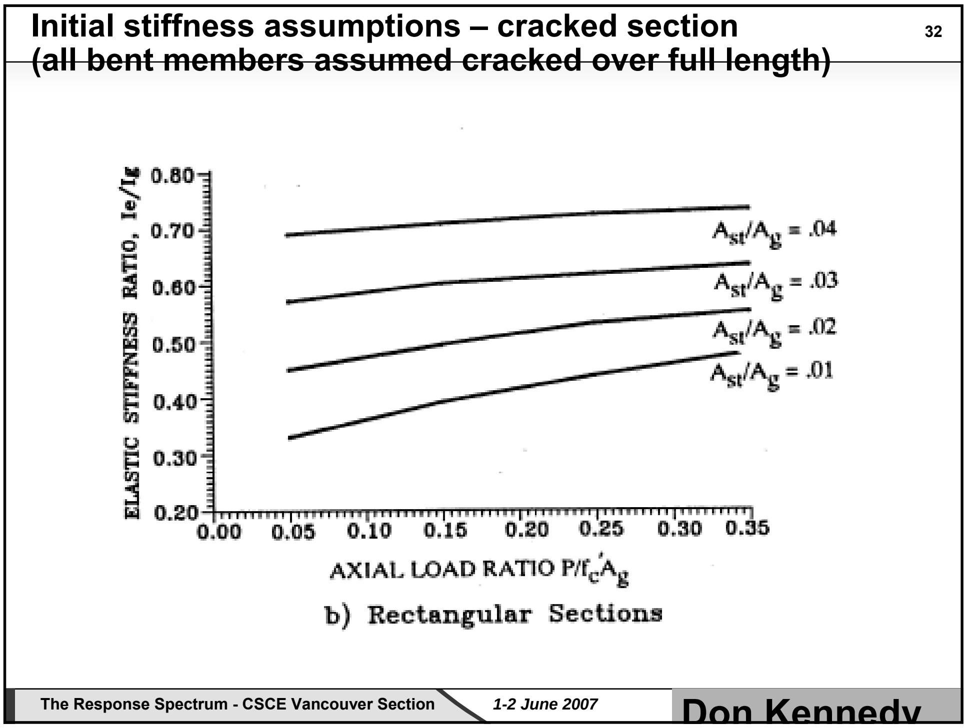
Effective stiffness at large displacement

Area in loops represent hysteretic damping



Initial vs secant stiffness assumptions

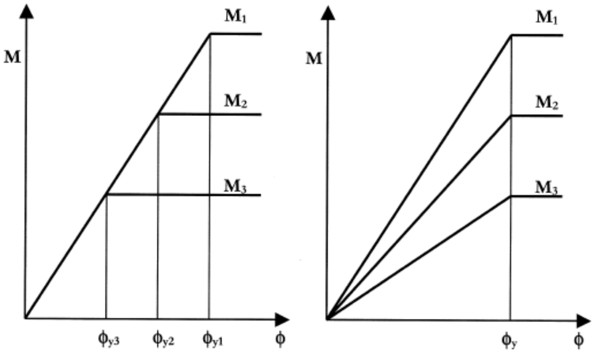
Figure 1. Illustration of initial-stiffness and secant stiffness concepts related to a structure's full non-linear response.



Initial stiffness assumptions – cracked section (all bent members assumed cracked over full length)

b) Rectangular Sections

Constant stiffness assumption

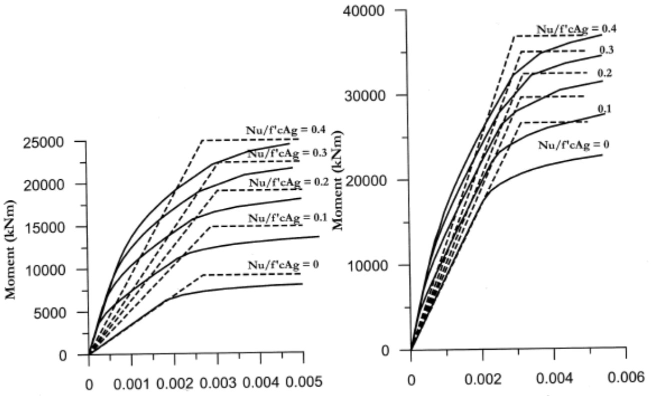


(a) Design Assumption
(constant stiffness)

(b) Realistic Conditions
(constant yield curvature)

Fig.2.2 Influence of Flexural Strength on Moment-Curvature Relationship

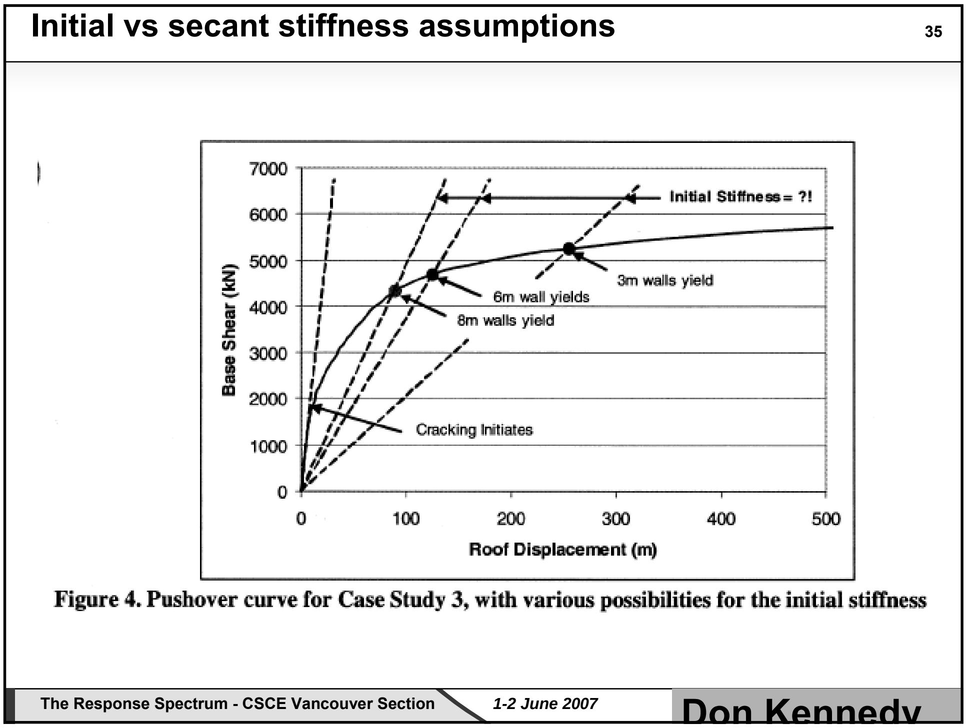
Constant stiffness assumption



(a) Reinforcement Ratio = 1`%

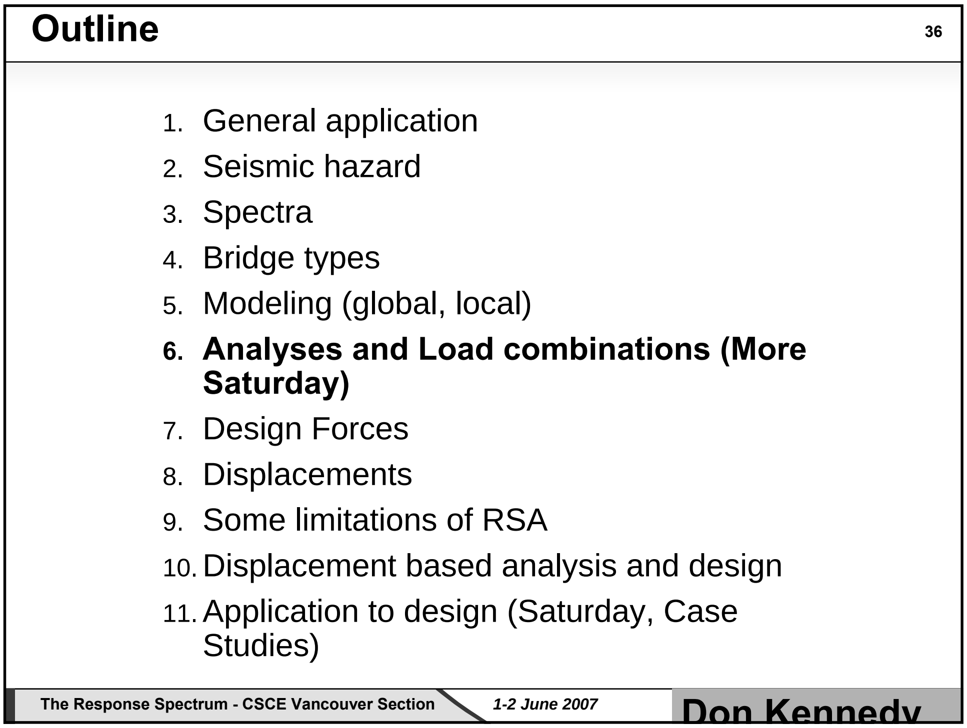
(b) Reinforcement Ratio = 3%

Fig. 2.6 Selected Moment-Curvature Curves for Rectangular Columns
($b=1.6m$, $h_c=1.6m$, $f'_c= 35MPa$, $f_y = 450MPa$)



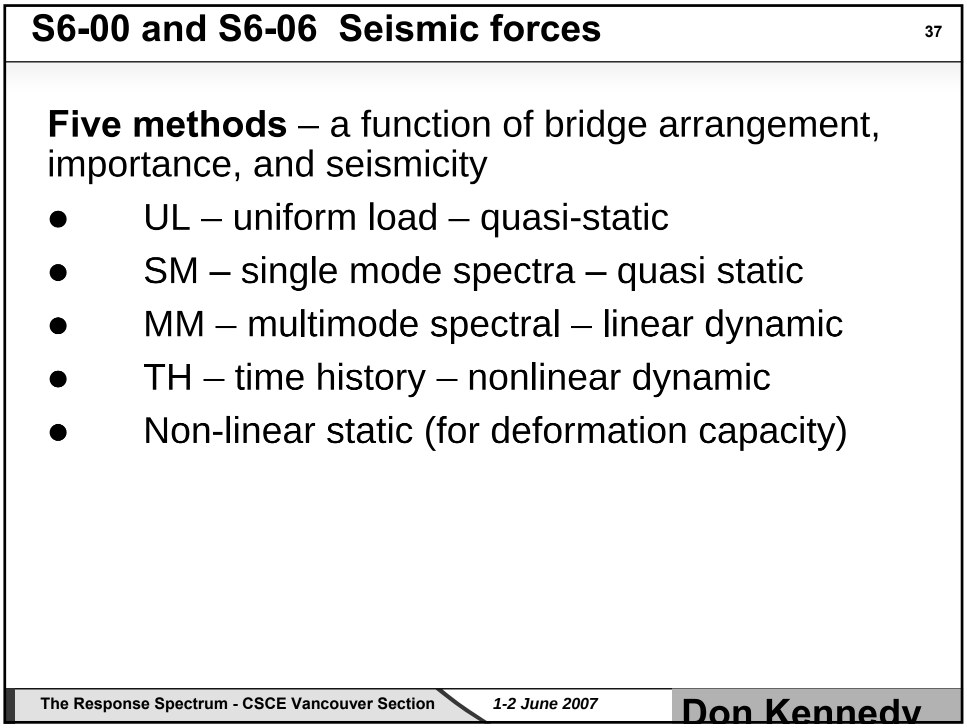
Initial vs secant stiffness assumptions

Figure 4. Pushover curve for Case Study 3, with various possibilities for the initial stiffness



Outline

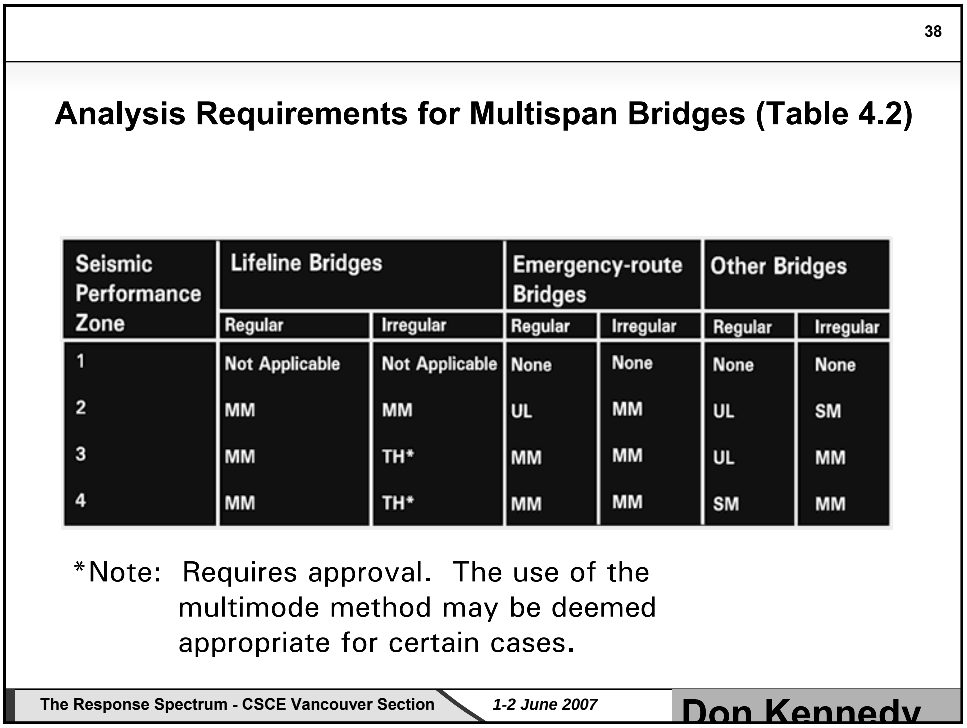
1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. **Analyses and Load combinations (More Saturday)**
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)



S6-00 and S6-06 Seismic forces

Five methods – a function of bridge arrangement, importance, and seismicity

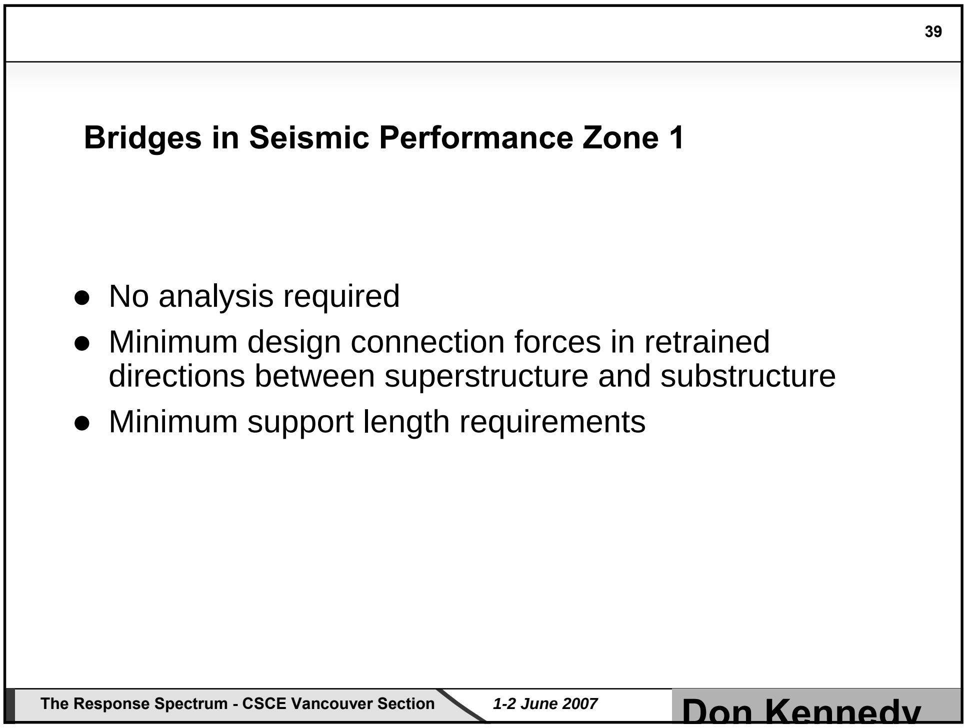
- UL – uniform load – quasi-static
- SM – single mode spectra – quasi static
- MM – multimode spectral – linear dynamic
- TH – time history – nonlinear dynamic
- Non-linear static (for deformation capacity)



Analysis Requirements for Multispan Bridges (Table 4.2)

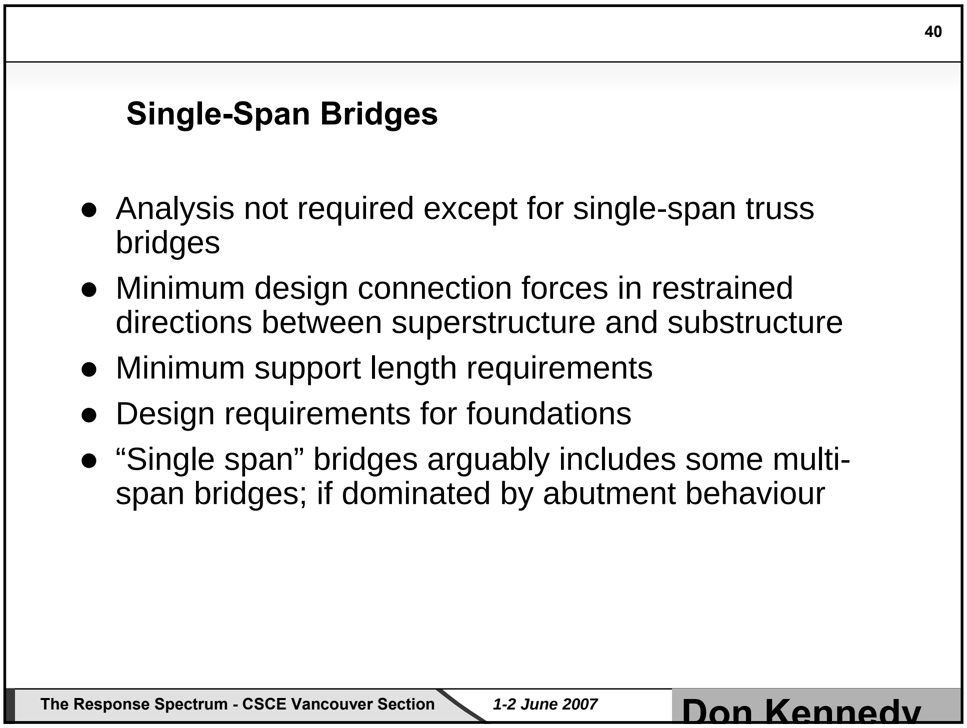
Seismic Performance Zone	Lifeline Bridges		Emergency-route Bridges		Other Bridges	
	Regular	Irregular	Regular	Irregular	Regular	Irregular
1	Not Applicable	Not Applicable	None	None	None	None
2	MM	MM	UL	MM	UL	SM
3	MM	TH*	MM	MM	UL	MM
4	MM	TH*	MM	MM	SM	MM

*Note: Requires approval. The use of the multimode method may be deemed appropriate for certain cases.



Bridges in Seismic Performance Zone 1

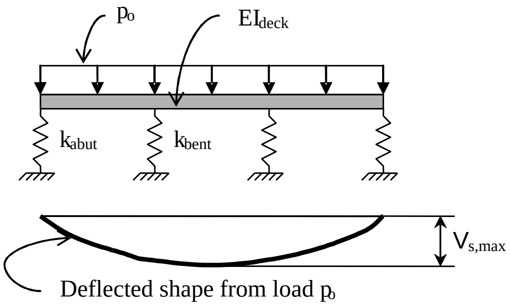
- No analysis required
- Minimum design connection forces in retrained directions between superstructure and substructure
- Minimum support length requirements



Single-Span Bridges

- Analysis not required except for single-span truss bridges
- Minimum design connection forces in restrained directions between superstructure and substructure
- Minimum support length requirements
- Design requirements for foundations
- “Single span” bridges arguably includes some multi-span bridges; if dominated by abutment behaviour

Uniform load method (to illustrate C_{sm})



Uniform load method (for C_{sm})

- $V_{s,max}$ is the maximum displacement caused by an arbitrary uniform load p_o

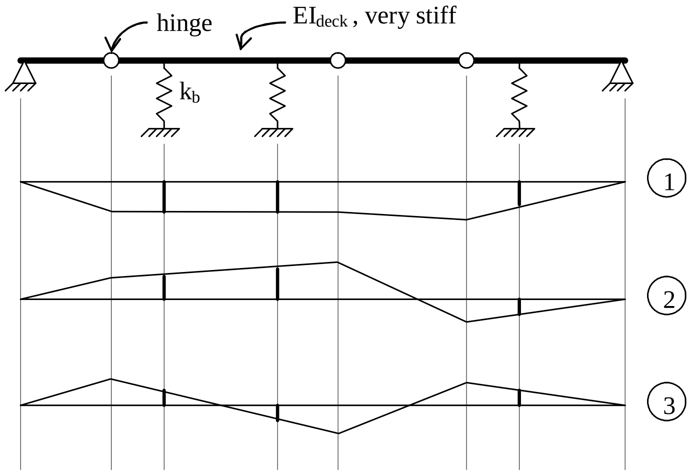
- $K = (p_o L) / v_{s,max}$ = structure stiffness
- $T = 2\pi (M / K)^{½} = 2\pi (W/(g K))^{1/2}$
- $p_e = C_{sm} W / L$, uniformly distributed load
  - where W = weight of bridge, L = length

Recalling that
$\omega = (K / M)^{1/2}$
$\omega T = 2\pi$

Multimode spectal analysis

- Most commonly used method of analysis
- Useful to start with or check using a 2-D model; model piers as springs (lump mass to deck), and with the deck modelled as a beam
- 3-D analysis has become common in bridge practice. Models can become complex
- Suggest progress from simple to increasingly complex only as requirements dictate
- Stiffness of piers and treatment of abutments important

2-D model – stiff deck – mode shapes



Earthquake Load Cases

- Combination of seismic effects in two perpendicular horizontal directions

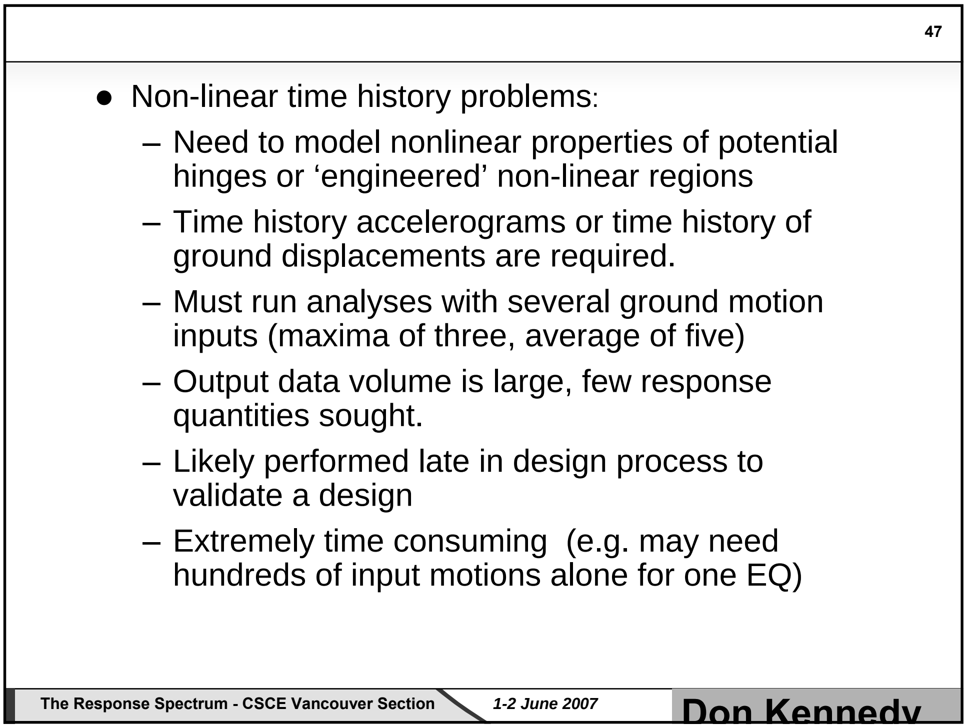
(a) 100% R_1 + 30% R_2
(b) 30% R_1 + 100% R_2

where R_1 = seismic demand in “1” direction from analysis in “1” direction
R_2 = seismic demand in “1” direction from analysis in “2” direction

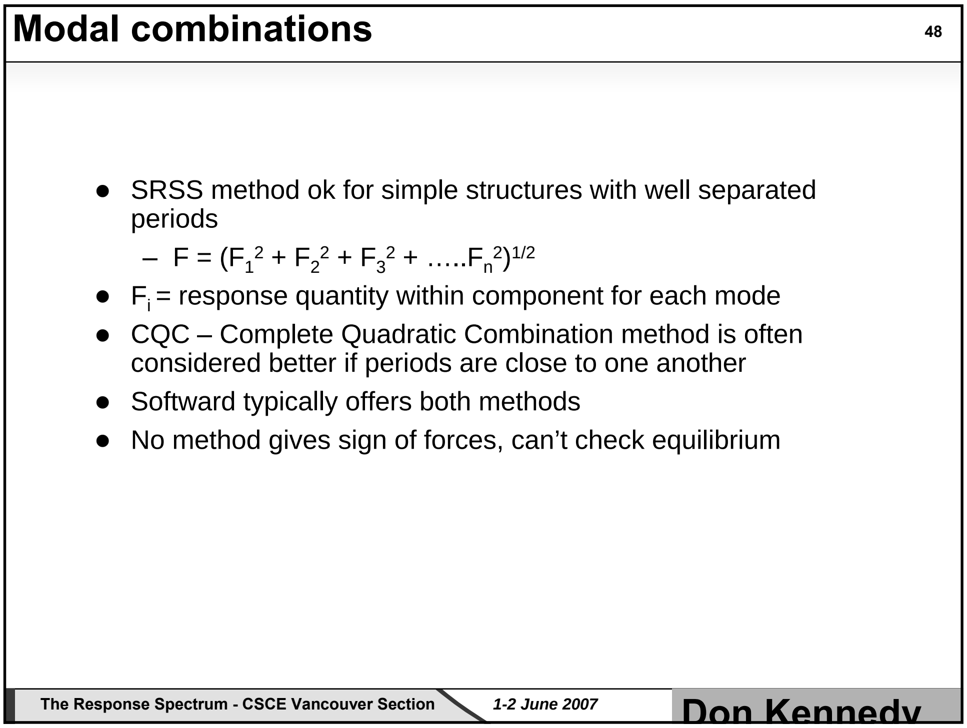
- Effects of vertical ground motion accounted for by DL factors of 0.8 and 1.25

TH- time history method

- Can be used as linear analyses if signs of members are important
- Required for nonlinear analysis, which may be needed because of:
  - different input motion at different bents (variable soil profile along long bridges)
  - Soil-structure interaction important (e.g. large diameter piles in soft soils)
  - expansion joints (especially for retrofit)
  - yielding of piers may alter global response, e.g. if bridge may become highly irregular in post-elastic range



- Non-linear time history problems:
  - Need to model nonlinear properties of potential hinges or ‘engineered’ non-linear regions
  - Time history accelerograms or time history of ground displacements are required.
  - Must run analyses with several ground motion inputs (maxima of three, average of five)
  - Output data volume is large, few response quantities sought.
  - Likely performed late in design process to validate a design
  - Extremely time consuming (e.g. may need hundreds of input motions alone for one EQ)



Modal combinations

- SRSS method ok for simple structures with well separated periods
  - $F = (F_1^2 + F_2^2 + F_3^2 + \ldots\ldots F_n^2)^{1/2}$
- F_i = response quantity within component for each mode
- CQC – Complete Quadratic Combination method is often considered better if periods are close to one another
- Softward typically offers both methods
- No method gives sign of forces, can’t check equilibrium

Seismic Hazard

- Code – C_{sm} function, design spectrum, includes soil and importance factors
- Site specific – uniform hazard response spectrum
- Based on 10% probability of exceedance in 50 years (475 year return period earthquake)

Longitudinal analysis

- Can always “define” longitudinal and transverse, but coupling of response can be essential in irregular bridges
- Same principles and methods apply as for transverse analysis
- Bridges are normally more flexible in longitudinal direction and displacements larger
- Behaviour of abutments and expansion joints complicates the analysis.
- Can bound analyses with “hinges free” and “hinges fixed”. Both have significant limitations, can give poor results.
- Abutments may control movement for short bridges

Bounded analyses for deformations (Mission Bridge)

Displacement based design

- Present codes are ‘force based’ with some checking of displacements
- ‘Displacement based’ design considers the *target* displacements and ductility demands on the members as design quantities.
- Stiffness in concrete piers is a function of strength, rather than a fraction of traditional moment of inertia
- Analysis and design process is therefore iterative.
- Must also adjust for effective damping to avoid over-conservatism
- Considered to be more logical and is straightforward
- “Myths and Fallacies”, 2003, Nigel Priestley
- Extensive literature (WCEE Auckland (2000), Rose School, etc).
- When will it find its way into bridge codes?
- Acceptable for two major bridge projects in B.C.

Outline

1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. **Design Forces (Friday and Saturday)**
8. Displacements
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)

Response modification factor - R

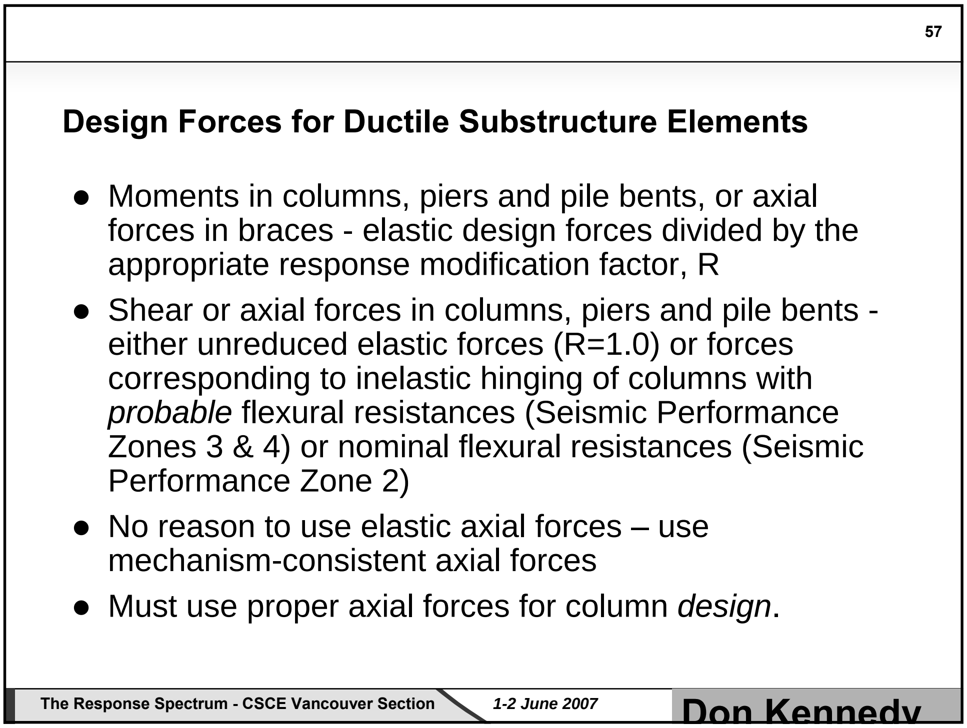
- R is related to the ductile capacity of members, varies from 2 for wall type piers and batter piles, to 5 for multiple column bents
- Depends on the flexural ductility of members and on redundancy
- Approximately equal to the displacement ductility of the structure
- May not even be close to the displacement ductility of the structure or representative of ductility demands on components
- Application to member proportioning is not as clear as it should be (hinge sequence / location)

Response Modification Factors

Ductile substructure elements	Response modification factor, R
Wall-type piers in direction of larger dimension	2.0
Reinforced concrete pile bents Vertical piles only	3.0
With batter piles	2.0
Single columns . Ductile reinforced concrete	3.0
Ductile steel	3.0
Steel or composite steel and concrete pile bents Vertical piles only	5.0
With batter piles	3.0
Multiple-column bents Ductile reinforced concrete	5.0
Ductile steel columns or frames	5.0
Braced frames Ductile steel braces	4.0
Nominally ductile steel braces	2.5

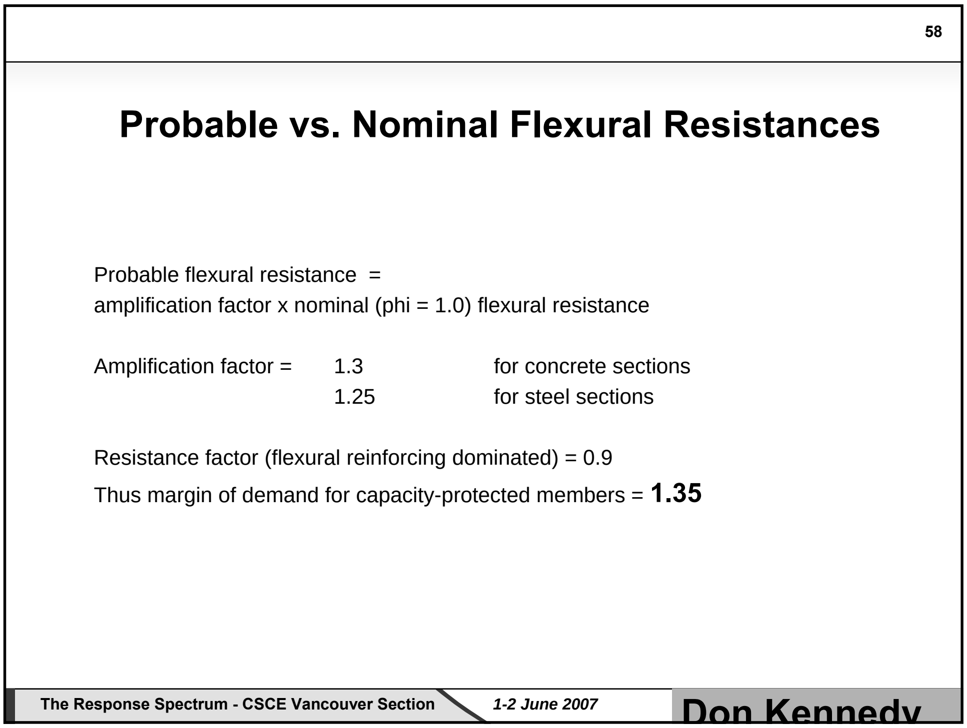
Design Philosophy

- General Philosophy of Capacity Design
  - Ascertain yielding mechanism in ductile substructures
  - Prevent undesirable failure modes
- Ductile Substructure Elements
- Capacity-Protected Elements
- N.B.: *Required* to have ductile sub-structure elements). Code should be made clearer
- Capacity design DOES de-sensitize most bridges from crudeness of elastic analyses



Design Forces for Ductile Substructure Elements

- Moments in columns, piers and pile bents, or axial forces in braces - elastic design forces divided by the appropriate response modification factor, R
- Shear or axial forces in columns, piers and pile bents - either unreduced elastic forces (R=1.0) or forces corresponding to inelastic hinging of columns with *probable* flexural resistances (Seismic Performance Zones 3 & 4) or nominal flexural resistances (Seismic Performance Zone 2)
- No reason to use elastic axial forces – use mechanism-consistent axial forces
- Must use proper axial forces for column *design*.



Probable vs. Nominal Flexural Resistances

Probable flexural resistance =
amplification factor x nominal (phi = 1.0) flexural resistance

Amplification factor =	1.3	for concrete sections
	1.25	for steel sections

Resistance factor (flexural reinforcing dominated) = 0.9

Thus margin of demand for capacity-protected members = **1.35**

Design Forces for Capacity-Protected Elements

- Elastic design forces (R=1.0)
- Maximum force effects developed by ductile substructure elements attaining their probable resistance (Seismic Performance Zones 3 & 4) or their nominal resistance (Seismic Performance Zone 2)
- MoT (BC) requires that capacity design principles are to be followed (no “out” on elastic forces: can be problematic for some bridges)

Outline

1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. **Displacements**
9. Some limitations of RSA
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)

Displacements

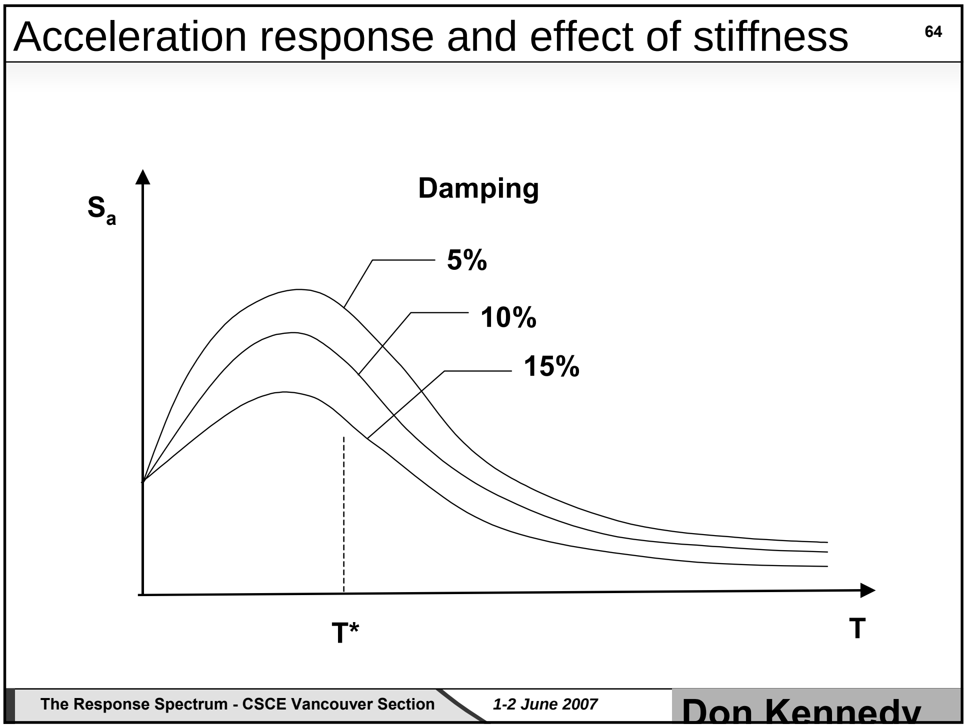
1. Ductile sub-structures….
2. Expansion joints
3. Supports
4. Bearings

Outline

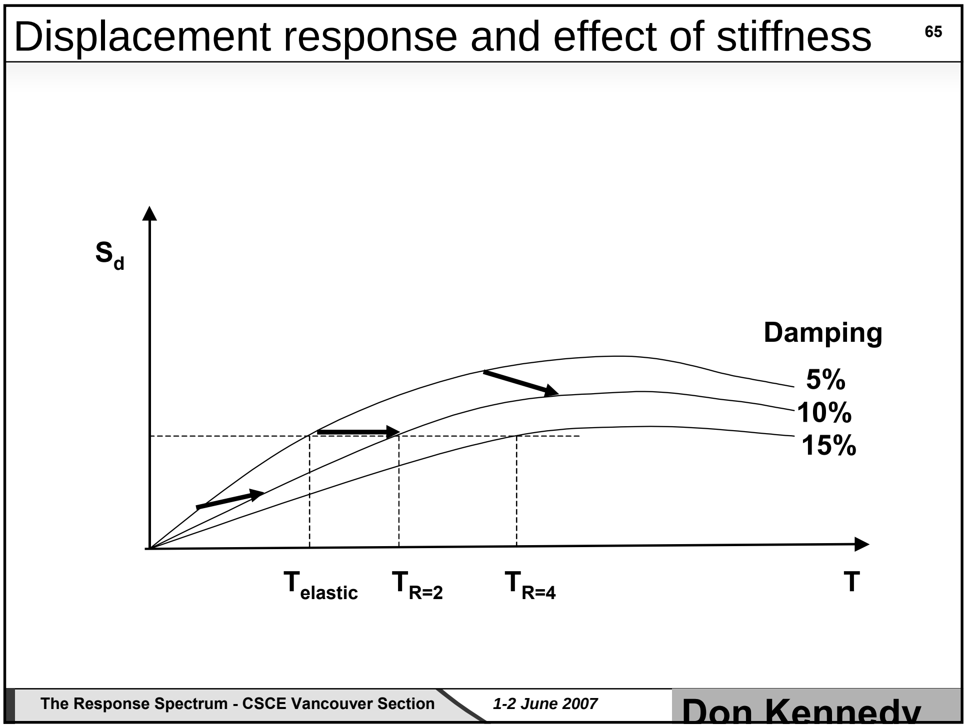
1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. **Some limitations of RSA**
10. Displacement based analysis and design
11. Application to design (Saturday, Case Studies)

Outline

1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. **Displacement based analysis and design**
11. Application to design (Saturday, Case Studies)



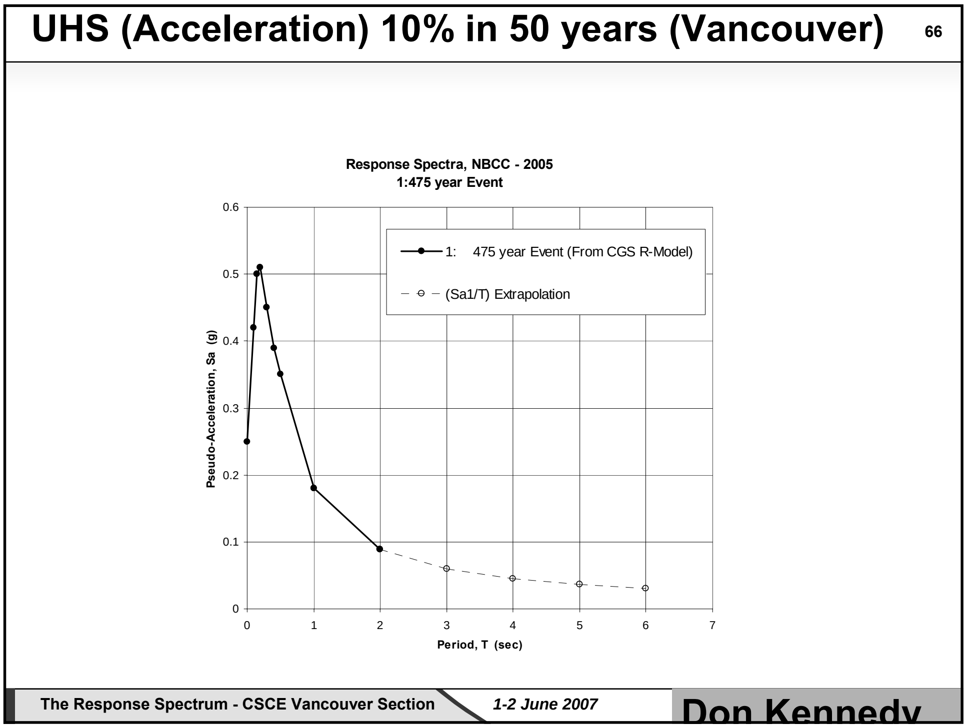
Acceleration response and effect of stiffness



Displacement response and effect of stiffness

65

The Response Spectrum - CSCE Vancouver Section *1-2 June 2007* **Don Kennedy**



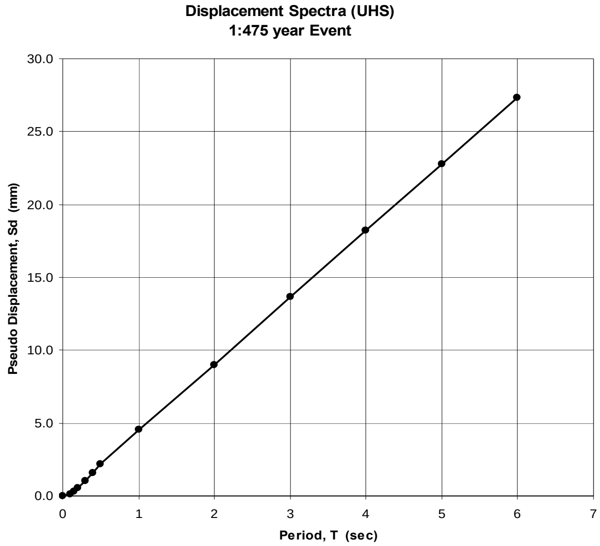
UHS (Acceleration) 10% in 50 years (Vancouver)

66

Response Spectra, NBCC - 2005
1:475 year Event

The Response Spectrum - CSCE Vancouver Section *1-2 June 2007* **Don Kennedy**

UHS (Acceleration) 10% in 50 years (Vancouver)



Outline

1. General application
2. Seismic hazard
3. Spectra
4. Bridge types
5. Modeling (global, local)
6. Analyses and Load combinations
7. Design Forces
8. Displacements
9. Some limitations of RSA
10. **Displacement based analysis and design**
11. **Application to design (Friday & Saturday)**