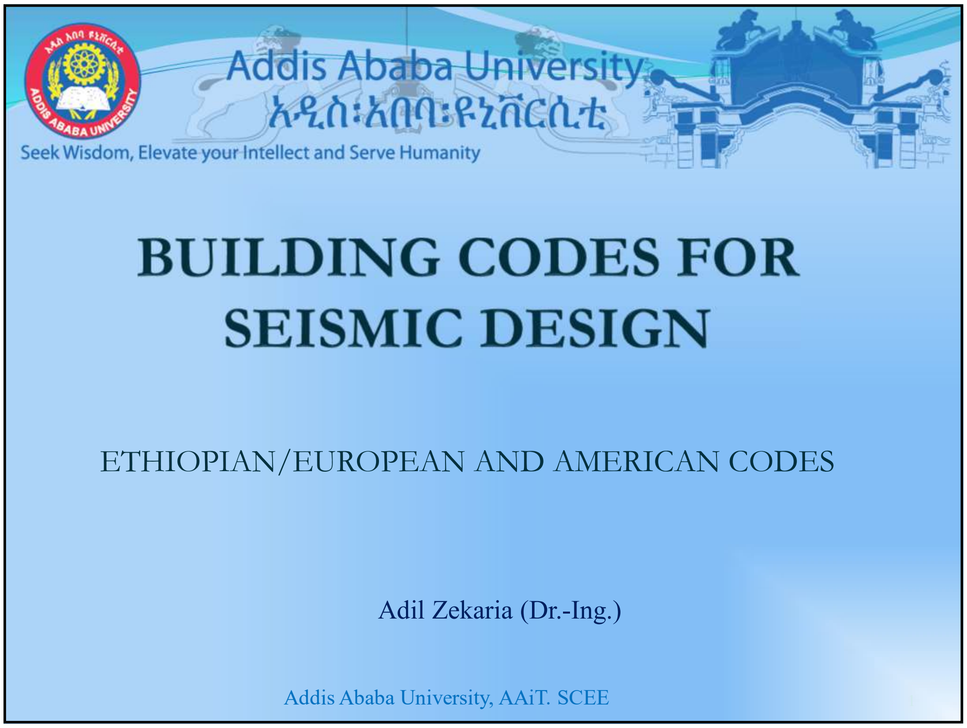

Addis Ababa University
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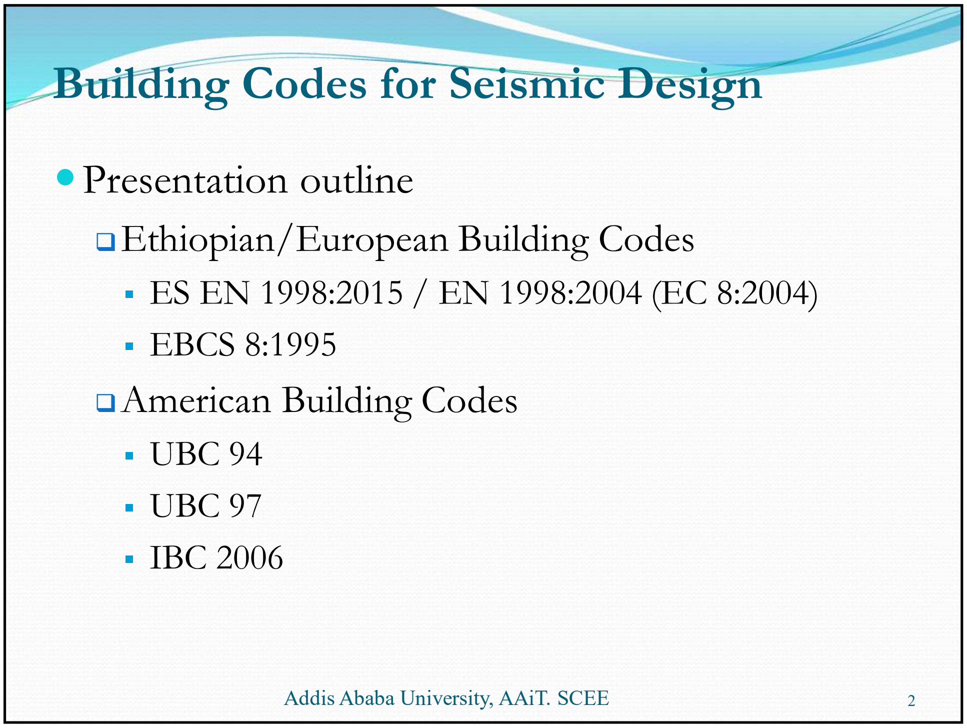
Seek Wisdom, Elevate your Intellect and Serve Humanity

BUILDING CODES FOR SEISMIC DESIGN

ETHIOPIAN/EUROPEAN AND AMERICAN CODES

Adil Zekaria (Dr.-Ing.)



Building Codes for Seismic Design

- Presentation outline
  - Ethiopian/European Building Codes
    - ES EN 1998:2015 / EN 1998:2004 (EC 8:2004)
    - EBCS 8:1995
  - American Building Codes
    - UBC 94
    - UBC 97
    - IBC 2006

Ethiopian/European Building Codes

ES EN 1998:2015/EN 1998:2004

EBCS 8:1995 (for comparison)

Ethiopian Code: ES EN 1998:2015

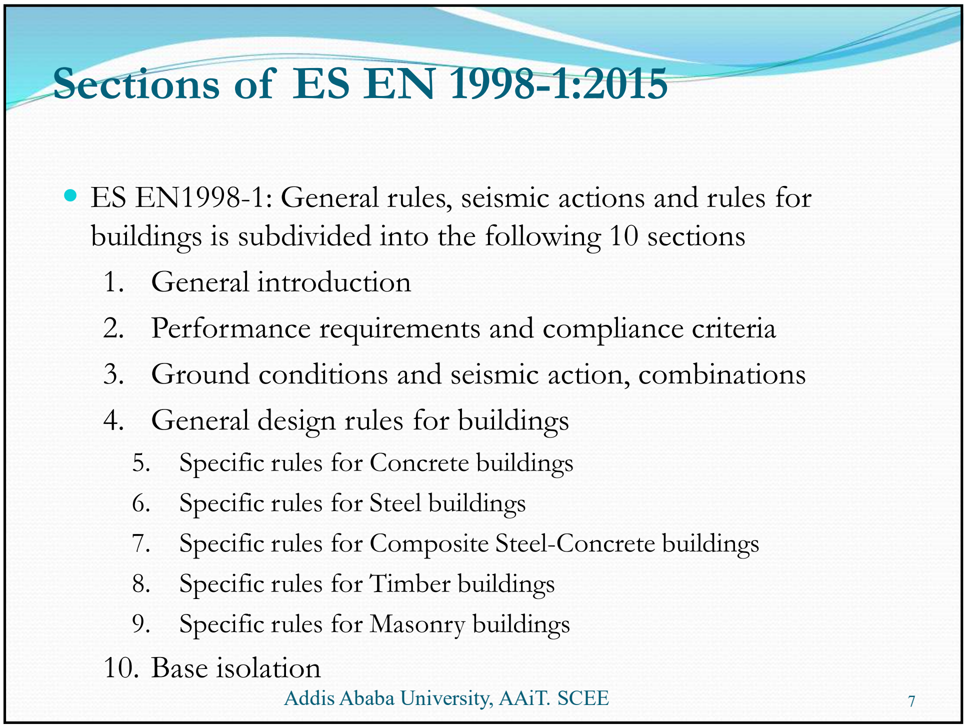
- The Ethiopian Government has signed agreement with the European Union's (EU) European Standardization Committee in 2011. (As a result Ethiopia can utilize the Eurocodes in the same manner as the other Member States of EU)
  - ❑ The major principles of the revised Ethiopian code (ES EN1998:2015) are the same as in the Eurocode EN 1998:2004.
  - ❑ During the development of the Eurocodes, there are procedures, values, or classes recommendations, for which an agreement could not be reached; these are the Nationally Determined Parameters (NDPs).
  - ❑ National Annexes may only contain information on those NDPs which are left open for national choice.

Scope of ES EN 1998:2015

- The purpose is to ensure that, in an event of an earthquake:
    - ❑ human lives are protected,
    - ❑ damage is limited, and
    - ❑ structures important for civil protection remain operational.
        - Note that the random nature of seismic events and the limited resource available to counter their effects makes the attainment of these goals partially possible and only measurable in probabilistic terms.
- Special structures, such as nuclear power plants, offshore structures and large dams, are beyond the scope of ES EN 1998

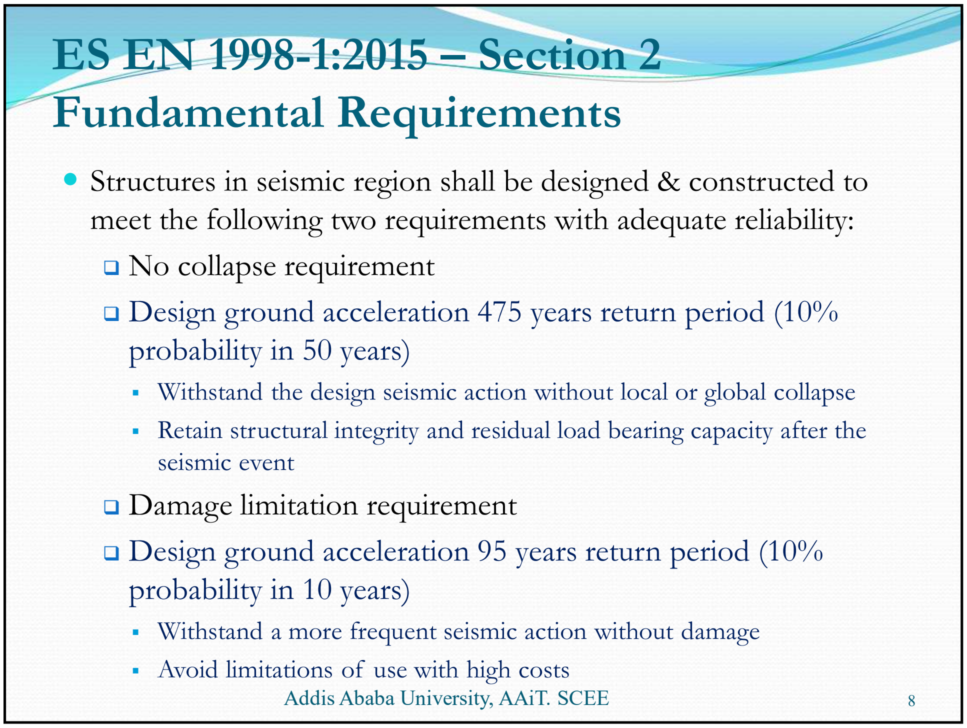
Parts of ES EN 1998:2015/EN 1998:2004

- EN 1998 - Design of structures for earthquake resistance has six parts:
    - ❑ EN1998-1: General rules, seismic actions and rules for buildings (This is the only published document Ethiopia code series as ES EN 1998-1:2015)
    - ❑ EN1998-2: Bridges
    - ❑ EN1998-3: Assessment and retrofitting of buildings
    - ❑ EN1998-4: Silos, tanks and pipelines
    - ❑ EN1998-5: Foundations, retaining structures and geotechnical aspects
    - ❑ EN1998-6: Towers, masts and chimneys



Sections of ES EN 1998-1:2015

- ES EN1998-1: General rules, seismic actions and rules for buildings is subdivided into the following 10 sections
  1. General introduction
  2. Performance requirements and compliance criteria
  3. Ground conditions and seismic action, combinations
  4. General design rules for buildings
  5. Specific rules for Concrete buildings
  6. Specific rules for Steel buildings
  7. Specific rules for Composite Steel-Concrete buildings
  8. Specific rules for Timber buildings
  9. Specific rules for Masonry buildings
  10. Base isolation



ES EN 1998-1:2015 – Section 2 Fundamental Requirements

- Structures in seismic region shall be designed & constructed to meet the following two requirements with adequate reliability:
  - ❑ No collapse requirement
  - ❑ Design ground acceleration 475 years return period (10% probability in 50 years)
    - ▪ Withstand the design seismic action without local or global collapse
    - ▪ Retain structural integrity and residual load bearing capacity after the seismic event
  - ❑ Damage limitation requirement
  - ❑ Design ground acceleration 95 years return period (10% probability in 10 years)
    - ▪ Withstand a more frequent seismic action without damage
    - ▪ Avoid limitations of use with high costs

ES EN 1998-1:2015 Compliance Criteria

- **In order to satisfy the fundamental requirements the following limit states shall be checked**
  - ❑ Ultimate limit states (ULS)
    - ULS are those associated with collapse or with other forms of structural failure which might endanger the safety of people.
  - ❑ Damage limitation states (DLS)
    - DLS are those associated with damages beyond which specified service requirements are no longer met.
  - ❑ Special measures
    - In order to limit the uncertainties and promote good behavior of structures for larger EQ, pertinent specific measures shall be taken.

ES EN 1998-1:2015 Compliance Criteria

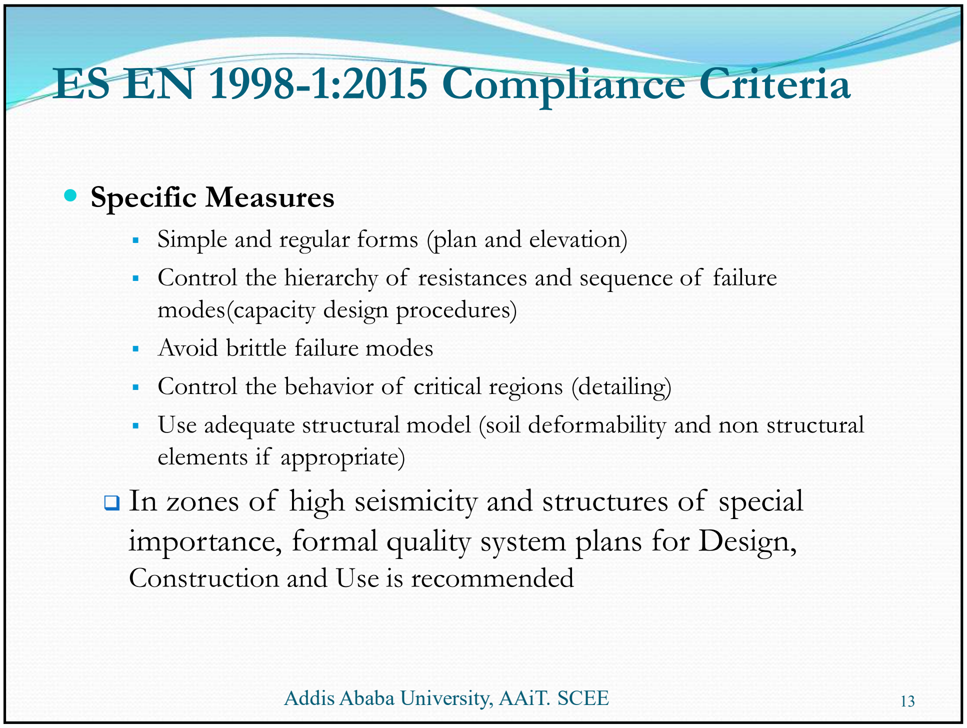
- ❑ Reduced or simplified design procedures for well defined categories of structures of low seismicity cases ($a_g < 0.08g$)
- ❑ No application of ES EN 1998 for very low seismicity cases ($a_g < 0.04g$)

ES EN 1998-1:2015 Compliance Criteria

- **Ultimate limit state**
    - Resistance and Energy dissipation capacity verification of the structural system
    - Appropriate Behavior factor values for the different ductility classes
    - Overturning and sliding stability check
    - Resistance of foundation elements and foundation soil without substantial permanent deformations
    - Second order effects shall be taken in to account
    - Non detrimental effect of non structural elements

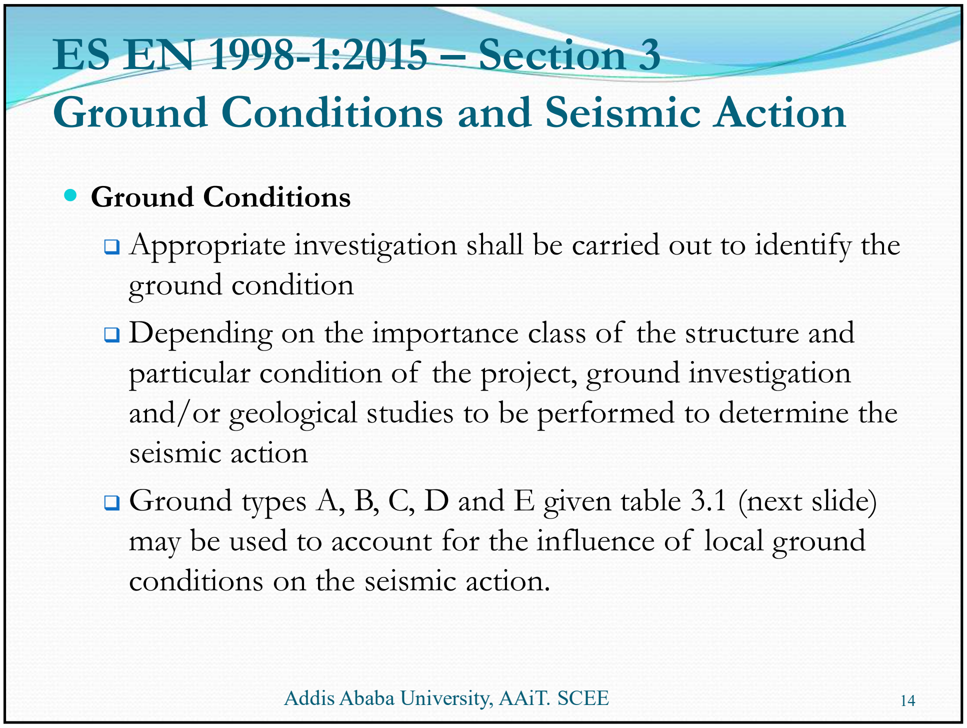
ES EN 1998-1:2015 Compliance Criteria

- **Damage limitation state**
    - Deformation limits (Maximum inter-story drift due to the "frequent" earthquake):
        - 0.5 %for brittle non structural elements attached to the structure
        - 0.75 %for ductile non structural elements attached to the structure
        - 1.0 %for non structural elements not interfering with the structure
    - Sufficient stiffness of the structure for the operationality of vital services and equipment
    - DLS may control the design in many cases



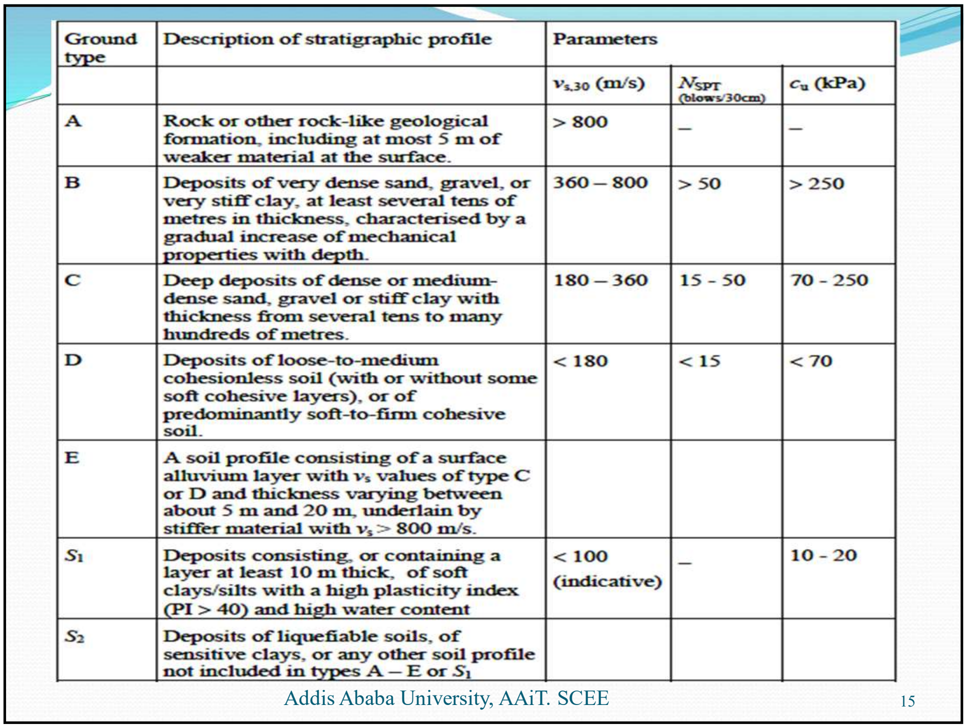
ES EN 1998-1:2015 Compliance Criteria

- **Specific Measures**
  - Simple and regular forms (plan and elevation)
  - Control the hierarchy of resistances and sequence of failure modes(capacity design procedures)
  - Avoid brittle failure modes
  - Control the behavior of critical regions (detailing)
  - Use adequate structural model (soil deformability and non structural elements if appropriate)
  - ❑ In zones of high seismicity and structures of special importance, formal quality system plans for Design, Construction and Use is recommended

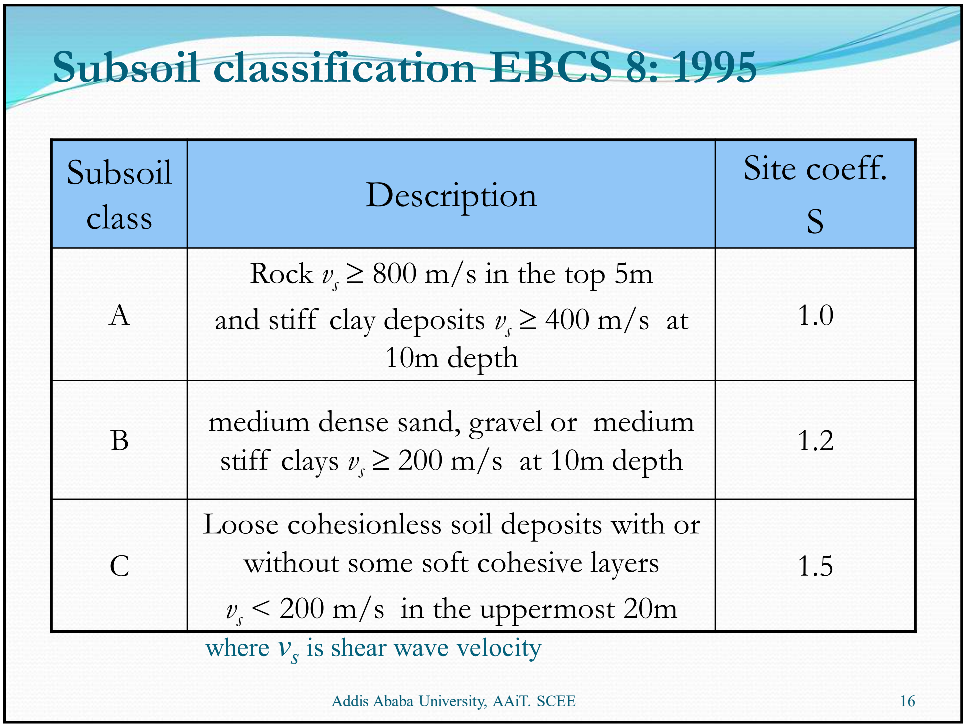


ES EN 1998-1:2015 – Section 3
Ground Conditions and Seismic Action

- **Ground Conditions**
  - ❑ Appropriate investigation shall be carried out to identify the ground condition
  - ❑ Depending on the importance class of the structure and particular condition of the project, ground investigation and/or geological studies to be performed to determine the seismic action
  - ❑ Ground types A, B, C, D and E given table 3.1 (next slide) may be used to account for the influence of local ground conditions on the seismic action.



Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	_	_
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.			
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (indicative)	_	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			



Subsoil classification EBCS 8: 1995

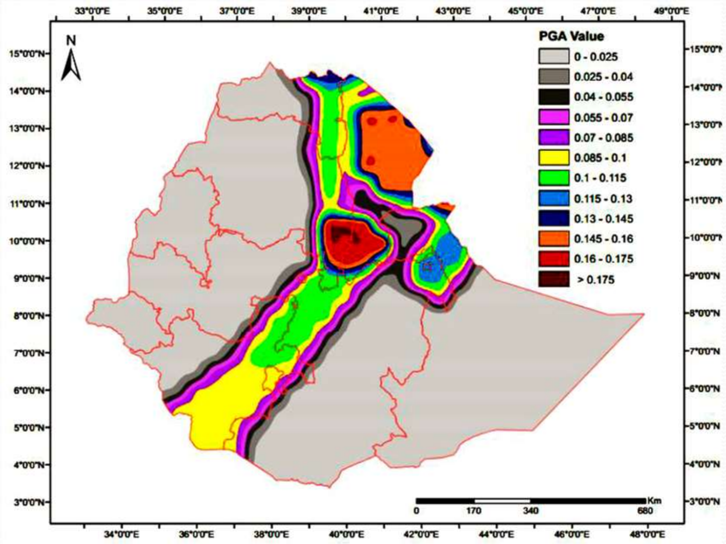
Subsoil class	Description	Site coeff. S
A	Rock $v_s \geq 800$ m/s in the top 5m and stiff clay deposits $v_s \geq 400$ m/s at 10m depth	1.0
B	medium dense sand, gravel or medium stiff clays $v_s \geq 200$ m/s at 10m depth	1.2
C	Loose cohesionless soil deposits with or without some soft cohesive layers $v_s < 200$ m/s in the uppermost 20m	1.5

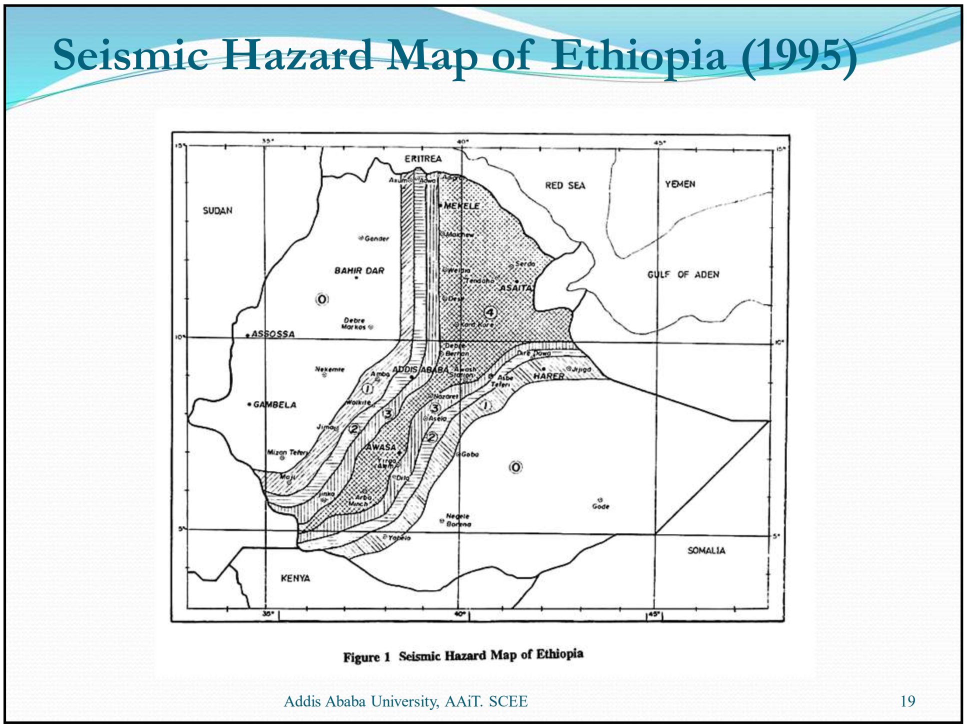
where v_s is shear wave velocity

ES EN 1998-1:2015 - Section 3
Ground Conditions and Seismic Action

- **Seismic Action**
  - ❑ National territories shall be subdivided into seismic zones depending on the local hazard
  - ❑ The hazard is described by the reference peak ground acceleration (PGA) on type A ground, a_{gR}
  - ❑ The design ground acceleration on type A ground a_g is equal to a_{gR} times the importance factor γ_I ($a_g = \gamma_I . a_{gR}$)
  - ❑ The seismic hazard map of the Ethiopia is shown in the next slide

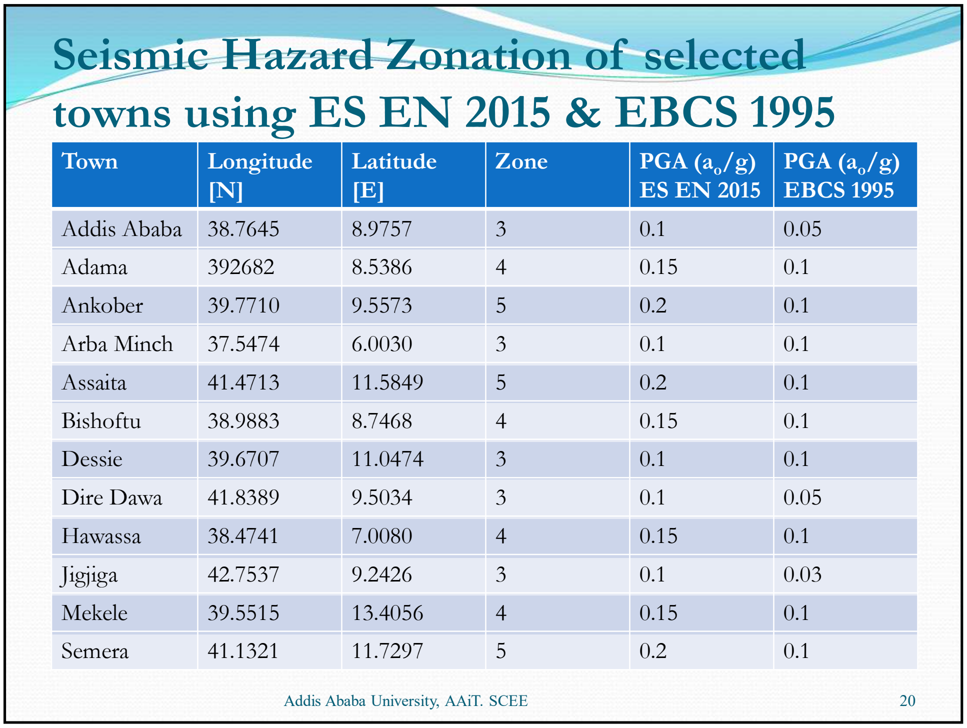
Seismic Hazard Map of Ethiopia (2015)





Seismic Hazard Map of Ethiopia (1995)

Figure 1 Seismic Hazard Map of Ethiopia

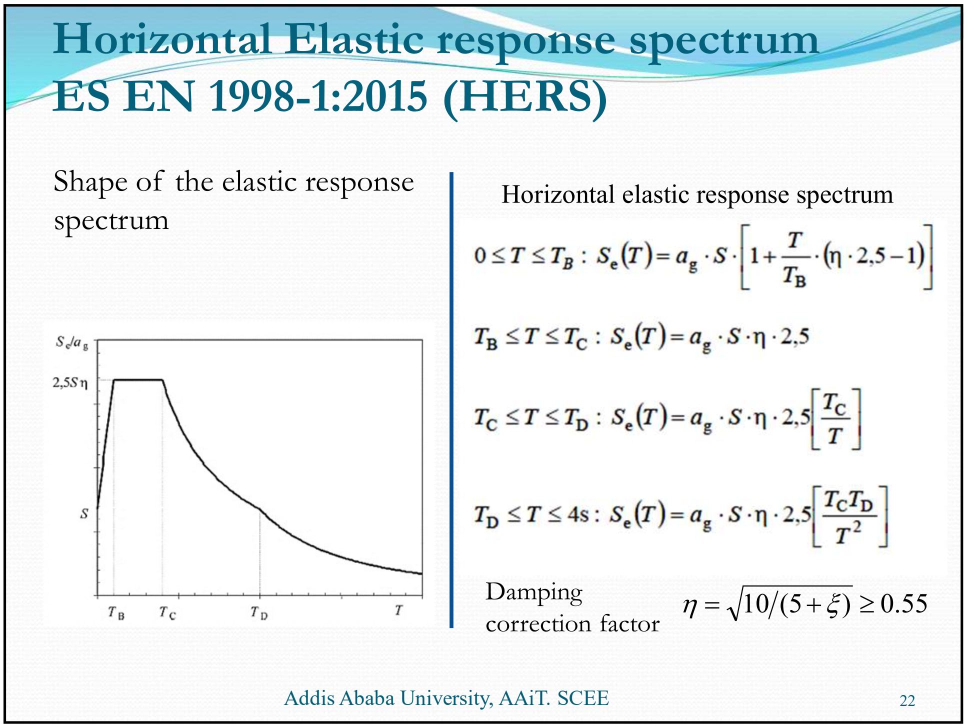


Seismic Hazard Zonation of selected towns using ES EN 2015 & EBCS 1995

Town	Longitude [N]	Latitude [E]	Zone	PGA (a_o/g) ES EN 2015	PGA (a_o/g) EBCS 1995
Addis Ababa	38.7645	8.9757	3	0.1	0.05
Adama	392682	8.5386	4	0.15	0.1
Ankober	39.7710	9.5573	5	0.2	0.1
Arba Minch	37.5474	6.0030	3	0.1	0.1
Assaita	41.4713	11.5849	5	0.2	0.1
Bishoftu	38.9883	8.7468	4	0.15	0.1
Dessie	39.6707	11.0474	3	0.1	0.1
Dire Dawa	41.8389	9.5034	3	0.1	0.05
Hawassa	38.4741	7.0080	4	0.15	0.1
Jigjiga	42.7537	9.2426	3	0.1	0.03
Mekele	39.5515	13.4056	4	0.15	0.1
Semera	41.1321	11.7297	5	0.2	0.1

ES EN 1998-1:2015 Representation of Seismic Action

- **Elastic response spectrum**
  - Horizontal elastic response spectrum
  - Vertical response spectrum
  - Design spectrum for elastic analysis
- **Time-history representation**
  - Artificial accelerograms
  - Recorded or simulated accelerograms
  - Spatial model of the seismic action
- Combination of the seismic action with other actions



Horizontal Elastic response spectrum ES EN 1998-1:2015 (HERS)

Shape of the elastic response spectrum

Horizontal elastic response spectrum

$$0 \le T \le T_B : S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2{,}5 - 1)\right]$$

$$T_B \le T \le T_C : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5$$

$$T_C \le T \le T_D : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\left[\frac{T_C}{T}\right]$$

$$T_D \le T \le 4\mathrm{s} : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\left[\frac{T_C T_D}{T^2}\right]$$

Damping correction factor $\eta = \sqrt{10/(5+\xi)} \ge 0.55$

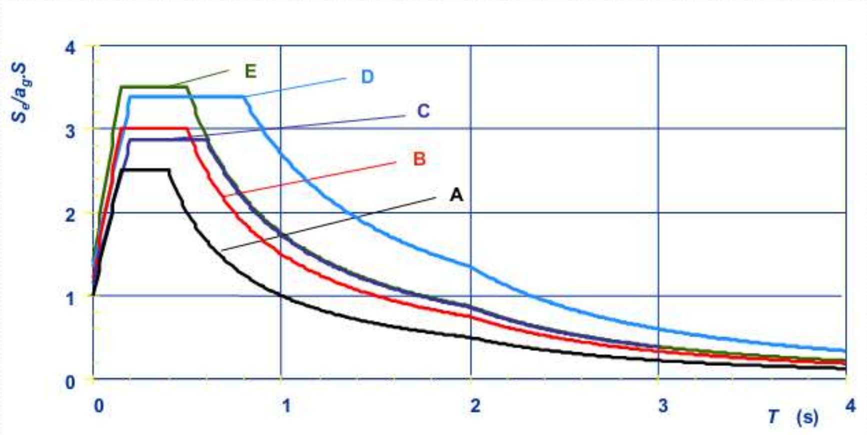
ES EN 1998-1:2015 (HERS Cont'd)

- If deep geology is not accounted for, the recommended choice is to use two types of spectra: type 1 and type 2.

- Design spectrum parameters: Type 1
- High and moderate seismicity region $M_s > 5.5$

Ground type	S	T_b	T_c	T_d
A (rock)	1.00	0.15	0.4	2.0
B (Very stiff soil)	1.20	0.15	0.5	2.0
C (medium stiff)	1.15	0.20	0.6	2.0
D (Soft soil)	1.35	0.20	0.8	2.0
E (thin Soft soil over rock)	1.40	0.15	0.5	2.0

ES EN 1998-1:2015 (HERS Cont'd)



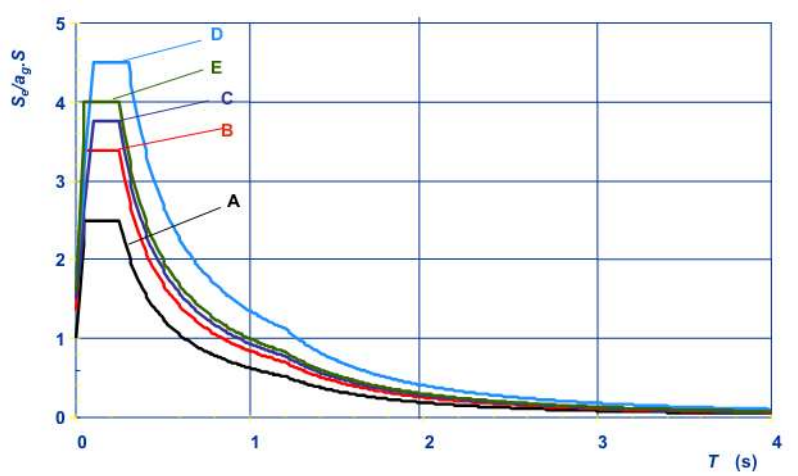
- Elastic response spectra for 5% damping for Type 1

ES EN 1998-1:2015 (HERS Cont'd)

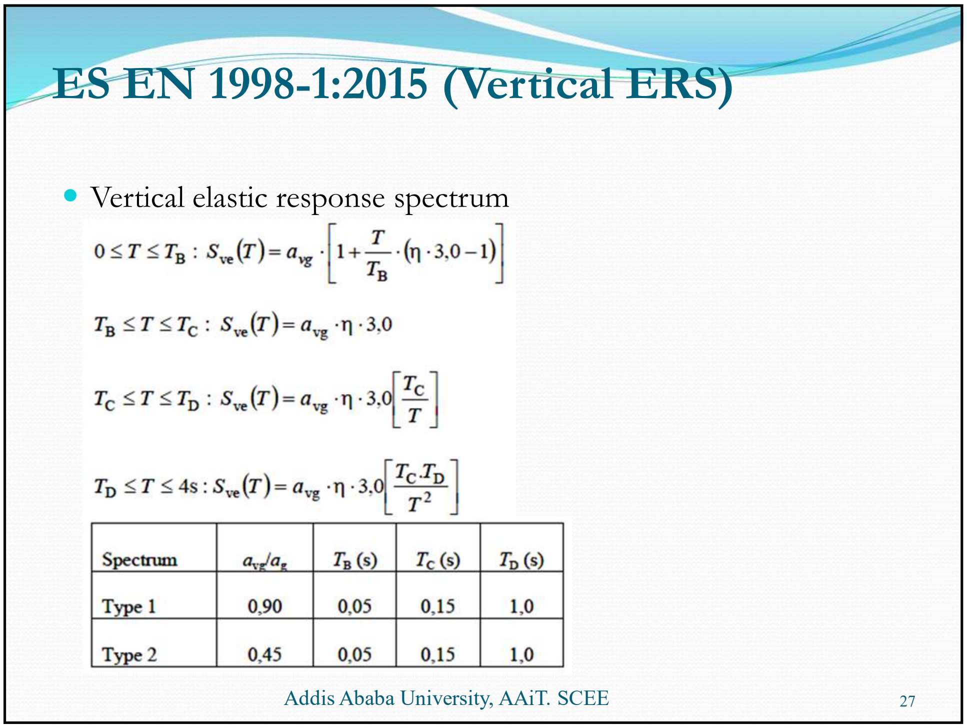
- Design spectrum parameters: Type 2
- Low seismicity region ($M_s \leq 5.5$); near field earthquakes

Ground type	S	T_b	T_c	T_d
A (rock)	1.00	0.05	0.25	1.20
B (Very stiff soil)	1.35	0.05	0.25	1.20
C (medium stiff)	1.50	0.10	0.25	1.20
D (Soft soil)	1.80	0.10	0.30	1.20
E (thin Soft soil over rock)	1.60	0.05	0.25	1.20

ES EN 1998-1:2015 (HERS Cont'd)



- Elastic response spectra for 5% damping for Type 2



ES EN 1998-1:2015 (Vertical ERS)

- Vertical elastic response spectrum

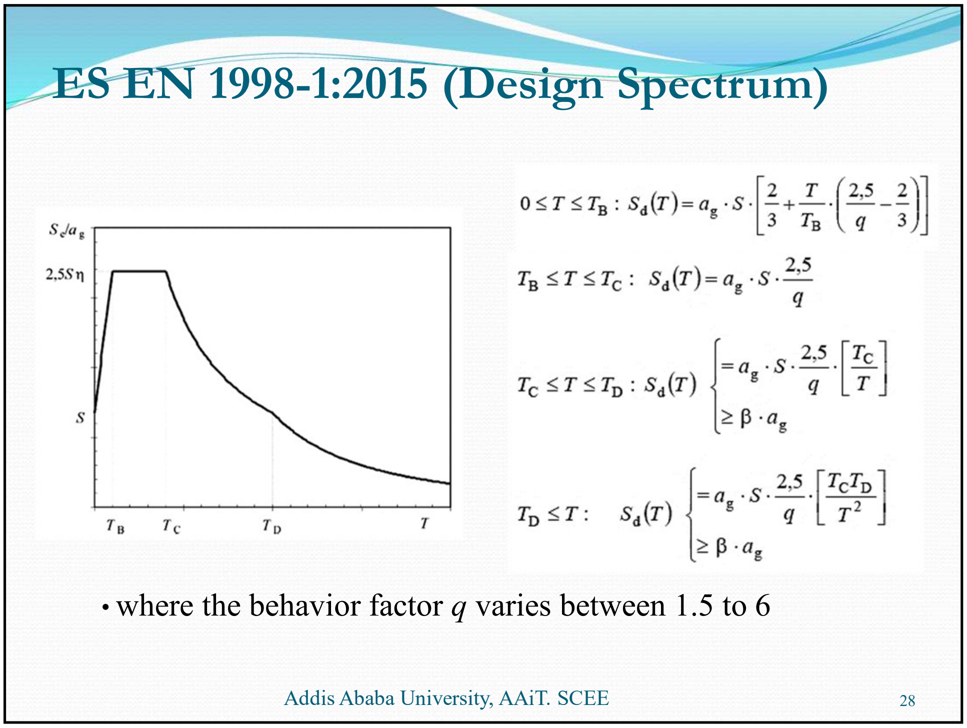
$$0 \le T \le T_{\mathrm{B}} : S_{\mathrm{ve}}(T) = a_{\mathrm{vg}} \cdot \left[1 + \frac{T}{T_{\mathrm{B}}} \cdot (\eta \cdot 3{,}0 - 1)\right]$$

$$T_{\mathrm{B}} \le T \le T_{\mathrm{C}} : S_{\mathrm{ve}}(T) = a_{\mathrm{vg}} \cdot \eta \cdot 3{,}0$$

$$T_{\mathrm{C}} \le T \le T_{\mathrm{D}} : S_{\mathrm{ve}}(T) = a_{\mathrm{vg}} \cdot \eta \cdot 3{,}0 \left[\frac{T_{\mathrm{C}}}{T}\right]$$

$$T_{\mathrm{D}} \le T \le 4\mathrm{s} : S_{\mathrm{ve}}(T) = a_{\mathrm{vg}} \cdot \eta \cdot 3{,}0 \left[\frac{T_{\mathrm{C}} \cdot T_{\mathrm{D}}}{T^2}\right]$$

Spectrum	a_{vg}/a_g	T_B (s)	T_C (s)	T_D (s)
Type 1	0,90	0,05	0,15	1,0
Type 2	0,45	0,05	0,15	1,0



ES EN 1998-1:2015 (Design Spectrum)

$$0 \le T \le T_{\mathrm{B}} : S_{\mathrm{d}}(T) = a_{\mathrm{g}} \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_{\mathrm{B}}} \cdot \left(\frac{2{,}5}{q} - \frac{2}{3}\right)\right]$$

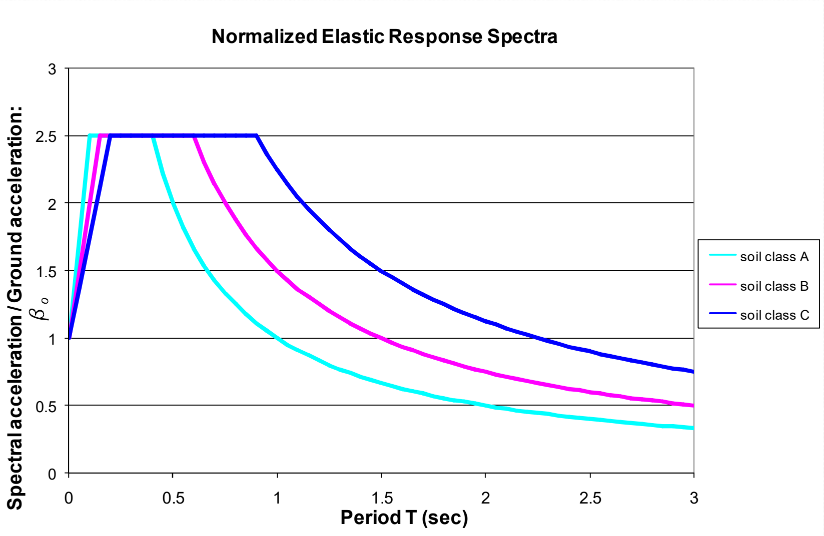
$$T_{\mathrm{B}} \le T \le T_{\mathrm{C}} : S_{\mathrm{d}}(T) = a_{\mathrm{g}} \cdot S \cdot \frac{2{,}5}{q}$$

$$T_{\mathrm{C}} \le T \le T_{\mathrm{D}} : S_{\mathrm{d}}(T) \begin{cases} = a_{\mathrm{g}} \cdot S \cdot \dfrac{2{,}5}{q} \cdot \left[\dfrac{T_{\mathrm{C}}}{T}\right] \\ \ge \beta \cdot a_{\mathrm{g}} \end{cases}$$

$$T_{\mathrm{D}} \le T : \quad S_{\mathrm{d}}(T) \begin{cases} = a_{\mathrm{g}} \cdot S \cdot \dfrac{2{,}5}{q} \cdot \left[\dfrac{T_{\mathrm{C}} T_{\mathrm{D}}}{T^2}\right] \\ \ge \beta \cdot a_{\mathrm{g}} \end{cases}$$

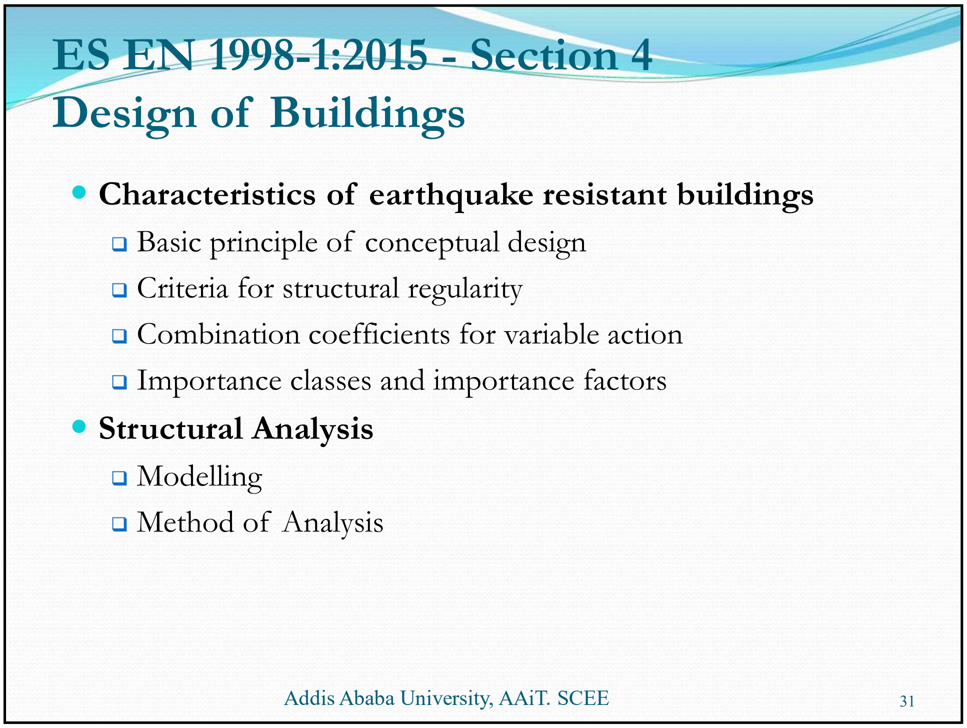
- where the behavior factor q varies between 1.5 to 6

Elastic Design Spectrum EBCS 8:1995



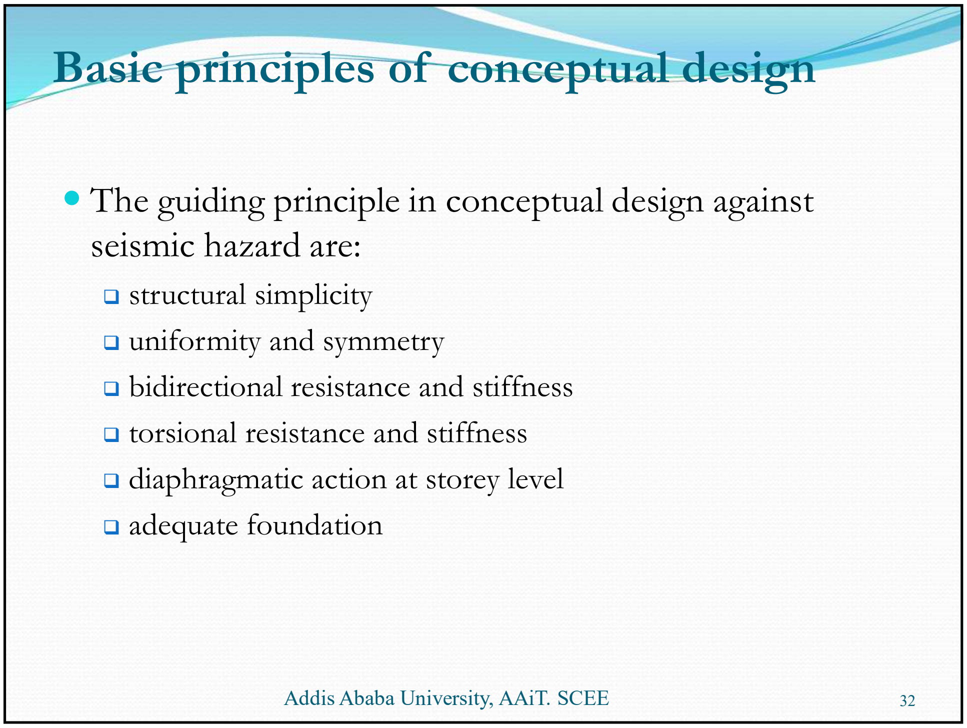
ES EN 1998-1:2015 (TH representation)

- **Alternative representations of the seismic action**
- Time history representation (essentially for NL analysis purposes)
- Three simultaneously acting accelerograms
  - Artificial accelerograms
    - **Match** the elastic response spectrum for 5% damping
    - **Duration** compatible with Magnitude ($T_s \geq 10$ s)
    - **Minimum number** of accelerograms: 3
  - Recorded or simulated accelerograms
    - **Scaled** to $a_g S$
    - **Match** the elastic response spectrum for 5% damping



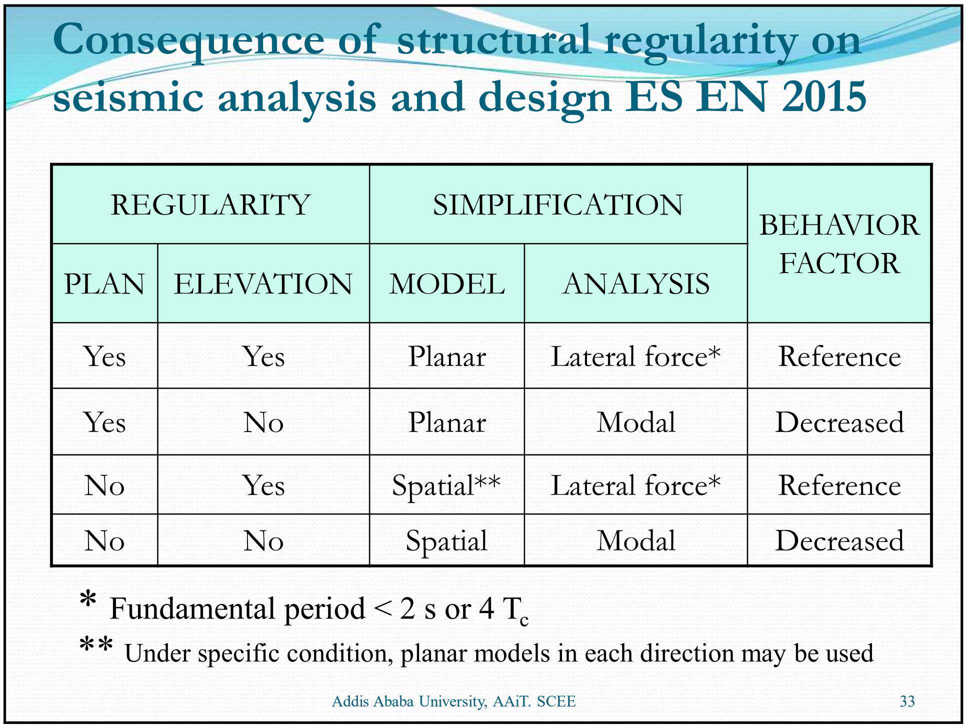
ES EN 1998-1:2015 - Section 4 Design of Buildings

- **Characteristics of earthquake resistant buildings**
  - ❑ Basic principle of conceptual design
  - ❑ Criteria for structural regularity
  - ❑ Combination coefficients for variable action
  - ❑ Importance classes and importance factors
- **Structural Analysis**
  - ❑ Modelling
  - ❑ Method of Analysis



Basic principles of conceptual design

- The guiding principle in conceptual design against seismic hazard are:
  - ❑ structural simplicity
  - ❑ uniformity and symmetry
  - ❑ bidirectional resistance and stiffness
  - ❑ torsional resistance and stiffness
  - ❑ diaphragmatic action at storey level
  - ❑ adequate foundation

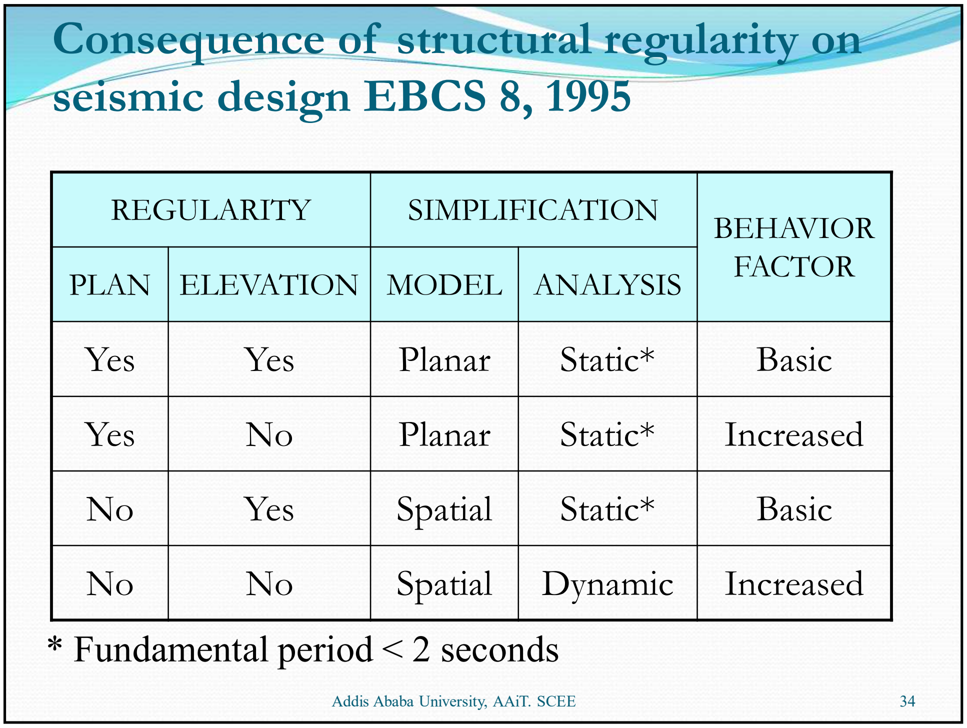


Consequence of structural regularity on seismic analysis and design ES EN 2015

REGULARITY		SIMPLIFICATION		BEHAVIOR FACTOR
PLAN	ELEVATION	MODEL	ANALYSIS	
Yes	Yes	Planar	Lateral force*	Reference
Yes	No	Planar	Modal	Decreased
No	Yes	Spatial**	Lateral force*	Reference
No	No	Spatial	Modal	Decreased

* Fundamental period < 2 s or 4 T_c

** Under specific condition, planar models in each direction may be used



Consequence of structural regularity on seismic design EBCS 8, 1995

REGULARITY		SIMPLIFICATION		BEHAVIOR FACTOR
PLAN	ELEVATION	MODEL	ANALYSIS	
Yes	Yes	Planar	Static*	Basic
Yes	No	Planar	Static*	Increased
No	Yes	Spatial	Static*	Basic
No	No	Spatial	Dynamic	Increased

* Fundamental period < 2 seconds

Regularity in Plan

- Symmetric in plan w.r.t. 2 orthogonal directions
- Plan configuration shall be compact (i.e floor area delimited by a polygonal convex line). Set-backs ≤ 5% of the floor area.
- In-plane stiffness of floors sufficiently large compared to stiffness of vertical elements. L, C, H, I and X plan shapes should be carefully examined.
- Slenderness of plan dimensions $\lambda = L_{max}/L_{min} \leq 4$

  where L_{max} and L_{min} are larger and smaller plan dimensions, measured in orthogonal directions

Regularity in Plan (Cont'd)

- At each level and for each direction of analysis x and y

$$e_{ox} \leq 0.30 \cdot r_x$$

$$r_x \geq l_s$$

Where

e_{ox} = distance between center of stiffness and center of mass

r_x = torsional radius

$$r_x = \sqrt{rotational\ stiffness / lateral\ stiffness}$$

l_s = radius of gyration of the floor mass

$$l_s = \sqrt{polar\ moment\ of\ inertia / mass}$$

Regularity in elevation

- All lateral load resisting systems run without interruption from foundation to top
- Both lateral stiffness & mass of story's remain constant or reduce gradually without abrupt changes
- ratio of actual storey resistance to required resistance should not vary disproportionately between adjacent storys.

Regularity in elevation (contd.)

when setbacks are present:

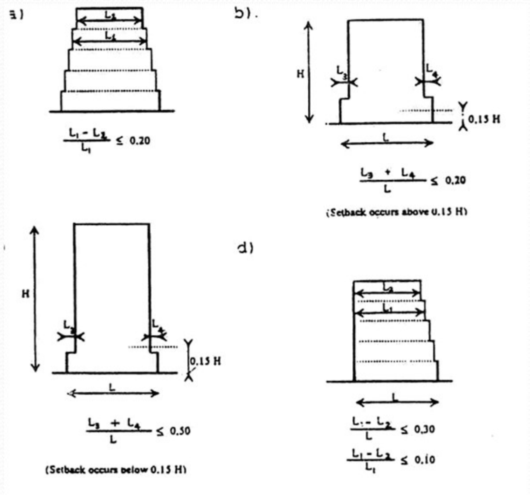


Figure 2.1 Criteria for Regularity of Setbacks

Combination coefficients for variable action

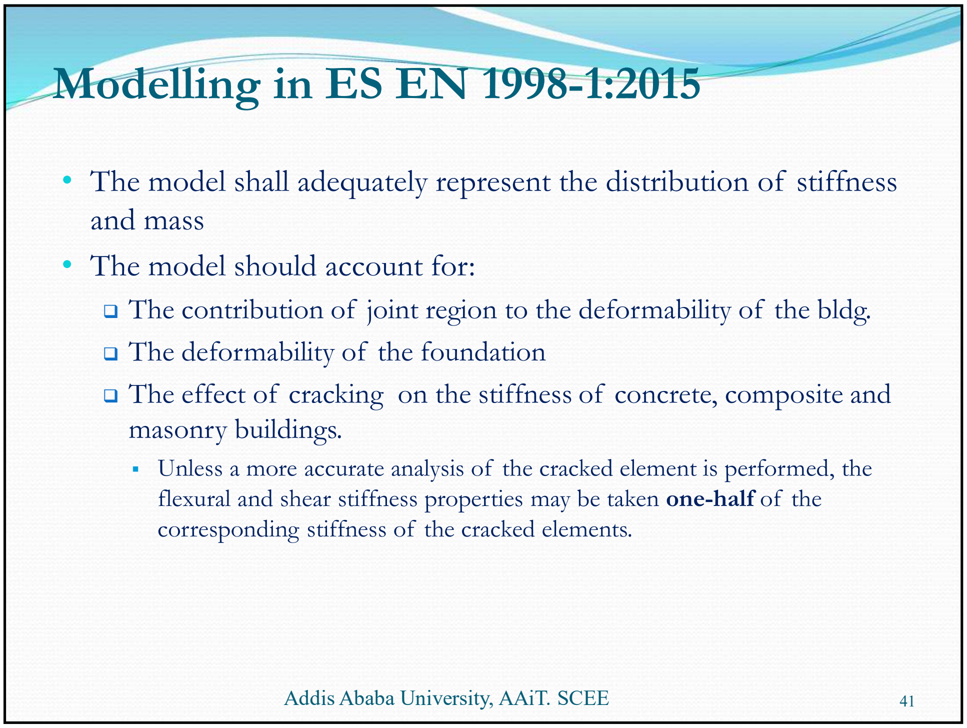
- The combination coefficients ψ_{2i} (for the quasi-permanent value of variable action q_i) for the design of buildings shall be those given in ES EN 1900:2015, Annex A1
- The combination coefficients ψ_{Ei} shall be computed from the following expression
    - ❑ $\psi_{Ei} = \varphi\psi_{2i}$

Type of variable action	Storey	φ
Categories A-C*	Roof Storeys with correlated occupancies Independently occupied storeys	1.0 0.8 0.5
Categories D-F* and Archives		1.0

* Categories as defined in ES EN1991-1-1:2015.

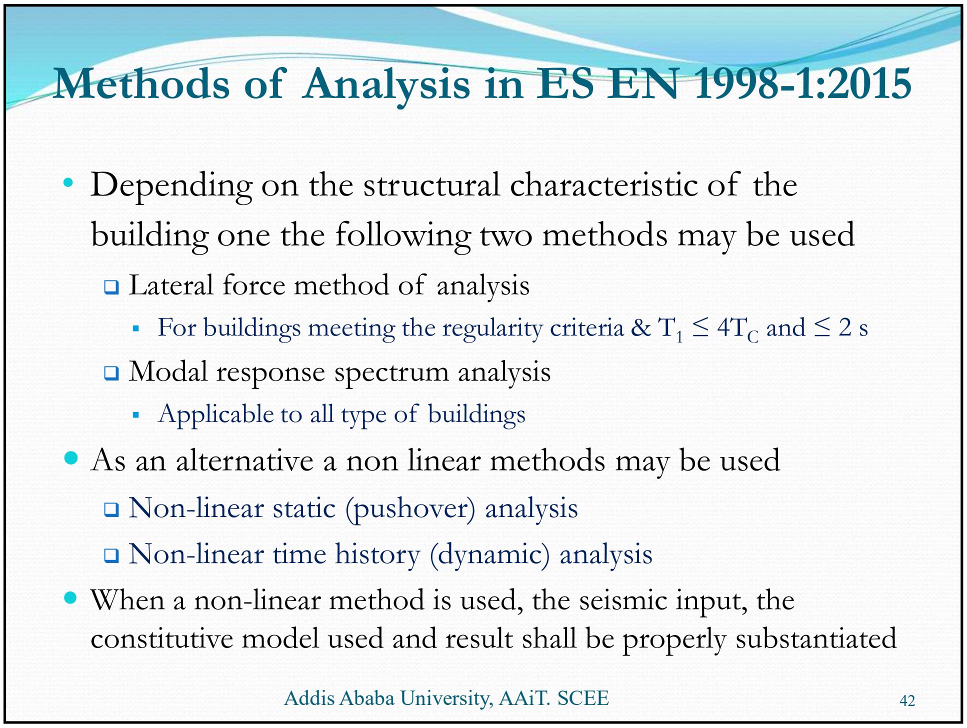
Importance classes and importance factors

Importance class	Buildings	Importance factor
I	Bldgs of minor importance for public safety, e.g. agricultural bldgs., etc.	0.8
II	ordinary buildings not belonging to other categories	1.0
III	Bldgs whose collapse results in serious consequence, e.g. schools, assembly halls,	1.2
IV	Bldgs whose integrity during EQ is of vital importance, e.g. hospitals, fire stations, power plants, etc	1.4



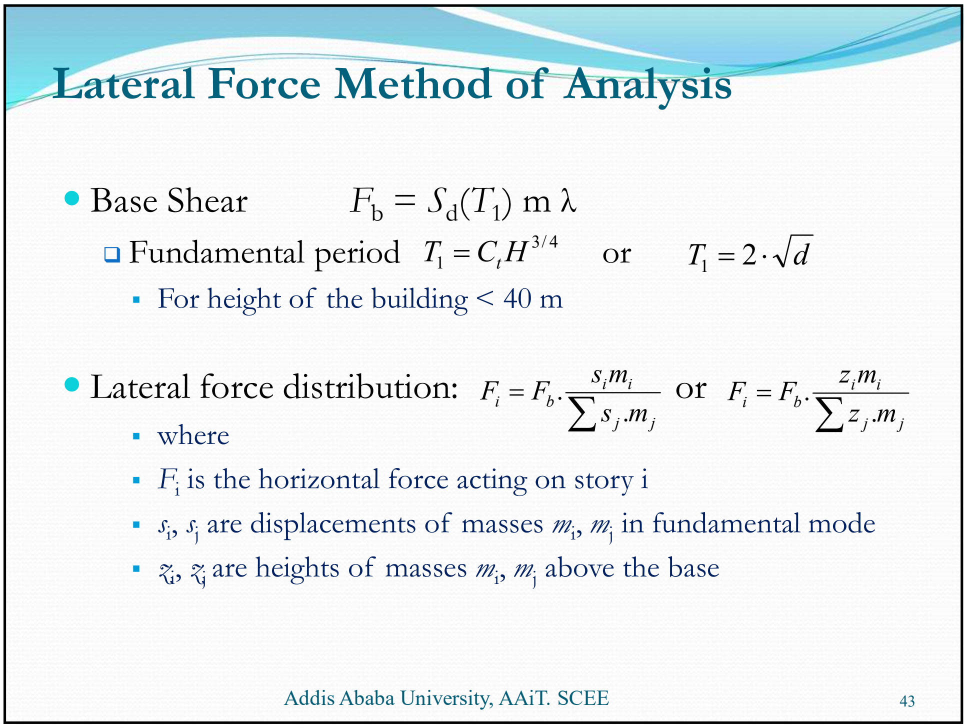
Modelling in ES EN 1998-1:2015

- The model shall adequately represent the distribution of stiffness and mass
- The model should account for:
  - ❑ The contribution of joint region to the deformability of the bldg.
  - ❑ The deformability of the foundation
  - ❑ The effect of cracking on the stiffness of concrete, composite and masonry buildings.
    - Unless a more accurate analysis of the cracked element is performed, the flexural and shear stiffness properties may be taken **one-half** of the corresponding stiffness of the cracked elements.



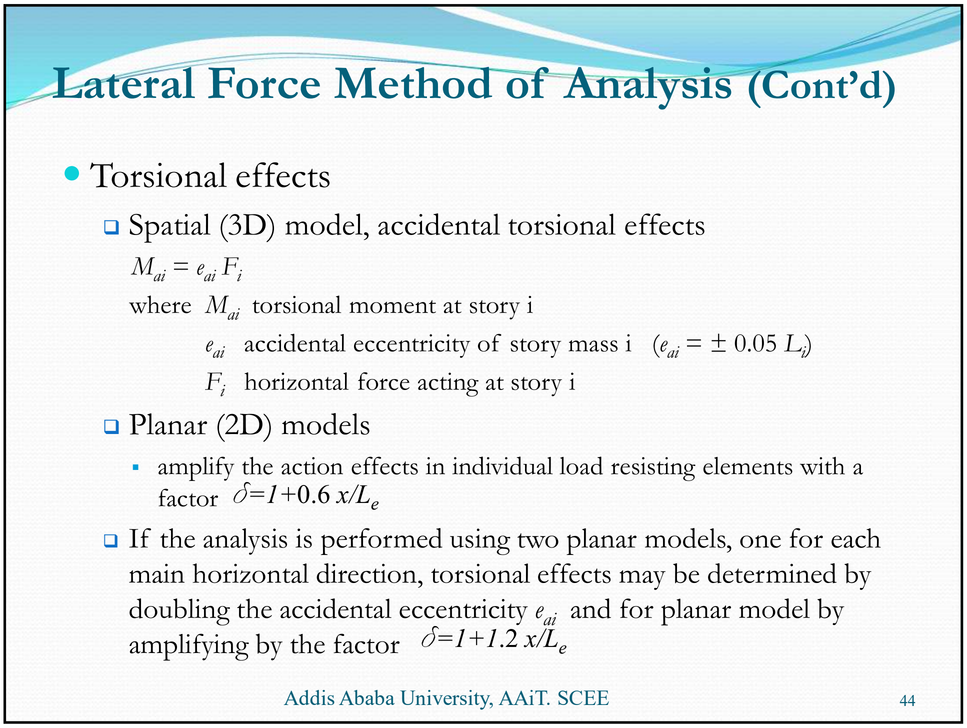
Methods of Analysis in ES EN 1998-1:2015

- Depending on the structural characteristic of the building one the following two methods may be used
  - ❑ Lateral force method of analysis
    - For buildings meeting the regularity criteria & $T_1 \leq 4T_C$ and ≤ 2 s
  - ❑ Modal response spectrum analysis
    - Applicable to all type of buildings
- As an alternative a non linear methods may be used
  - ❑ Non-linear static (pushover) analysis
  - ❑ Non-linear time history (dynamic) analysis
- When a non-linear method is used, the seismic input, the constitutive model used and result shall be properly substantiated



Lateral Force Method of Analysis

- Base Shear $F_b = S_d(T_1)\ m\ \lambda$
  - ❑ Fundamental period $T_1 = C_t H^{3/4}$ or $T_1 = 2 \cdot \sqrt{d}$
    - For height of the building < 40 m
- Lateral force distribution: $F_i = F_b \cdot \frac{s_i m_i}{\sum s_j . m_j}$ or $F_i = F_b \cdot \frac{z_i m_i}{\sum z_j . m_j}$
  - where
  - F_i is the horizontal force acting on story i
  - s_i, s_j are displacements of masses m_i, m_j in fundamental mode
  - z_i, z_j are heights of masses m_i, m_j above the base



Lateral Force Method of Analysis (Cont'd)

- Torsional effects
  - ❑ Spatial (3D) model, accidental torsional effects

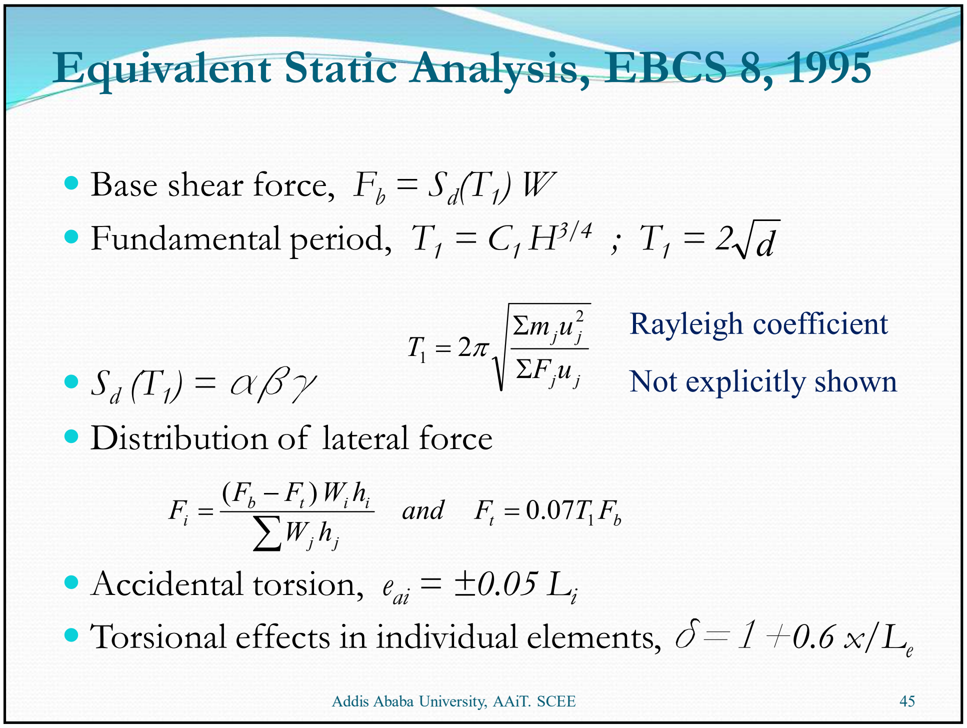
$M_{ai} = e_{ai} F_i$

where M_{ai} torsional moment at story i

e_{ai} accidental eccentricity of story mass i ($e_{ai} = \pm\ 0.05\ L_i$)

F_i horizontal force acting at story i

  - ❑ Planar (2D) models
    - amplify the action effects in individual load resisting elements with a factor $\delta = 1 + 0.6\ x/L_e$
  - ❑ If the analysis is performed using two planar models, one for each main horizontal direction, torsional effects may be determined by doubling the accidental eccentricity e_{ai} and for planar model by amplifying by the factor $\delta = 1 + 1.2\ x/L_e$



Equivalent Static Analysis, EBCS 8, 1995

- Base shear force, $F_b = S_d(T_1)\,W$
- Fundamental period, $T_1 = C_1 H^{3/4}$; $T_1 = 2\sqrt{d}$

$$T_1 = 2\pi\sqrt{\frac{\Sigma m_j u_j^2}{\Sigma F_j u_j}}$$

Rayleigh coefficient

Not explicitly shown

- $S_d(T_1) = \alpha\beta\gamma$
- Distribution of lateral force

$$F_i = \frac{(F_b - F_t)\,W_i h_i}{\sum W_j h_j} \quad and \quad F_t = 0.07 T_1 F_b$$

- Accidental torsion, $e_{ai} = \pm 0.05\, L_i$
- Torsional effects in individual elements, $\delta = 1 + 0.6\, x/L_e$

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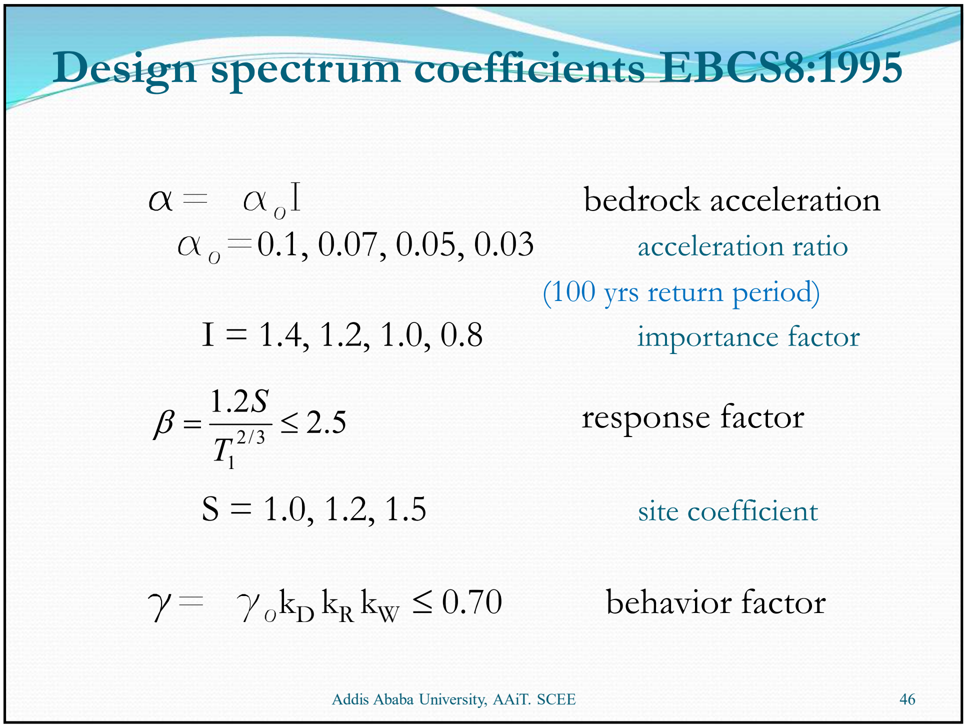

Design spectrum coefficients EBCS8:1995

$\alpha = \alpha_o I$ bedrock acceleration

$\alpha_o = 0.1, 0.07, 0.05, 0.03$ acceleration ratio

(100 yrs return period)

$I = 1.4, 1.2, 1.0, 0.8$ importance factor

$\beta = \frac{1.2S}{T_1^{2/3}} \leq 2.5$ response factor

$S = 1.0, 1.2, 1.5$ site coefficient

$\gamma = \gamma_o k_D k_R k_W \leq 0.70$ behavior factor

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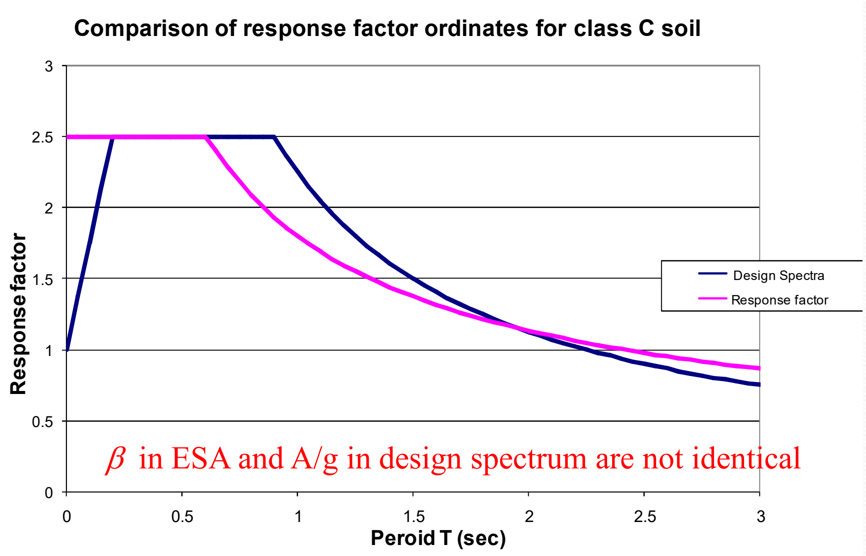
Comparing acceleration coefficients EBCS 8:1995


Comparison of response factor ordinates for class C soil

β in ESA and A/g in design spectrum are not identical

Modal response spectrum Analysis

- The response of all modes contributing significantly to the global response shall be considered
  - Those modes shall be considered for which:
    - The sum of the modal masses is at least 90% of the total building mass, i.e. $\sum m_i \geq 0.9 \cdot m_{tot}$
    - The modal mass is larger than 5% of the total building mass

$$m_i \geq 0.05 \cdot m_{tot}$$

  - If the above two requirements can not be fulfilled

$$k \geq 3 \cdot \sqrt{n} \quad \text{and} \quad T_k \leq 0.20\,s$$

    - The number of ***k*** modes to be taken for ***n*** story building

where T_k is the period of vibration of mode k.

Modal response spectrum Analysis (Contd)

- Combination of modal responses
  - The response in two vibration modes ***i*** and ***j*** are independent of each other if their periods satisfy $T_j \leq 0.9\ T_i$ condition
  - The maximum action effect from modes independent of each other is obtained from

    i.e. using SRSS combination rule $E_E = \sqrt{\Sigma E_{Ei}^2}$
  - If the $T_j \leq 0.9\ T_i$ condition is not satisfied more accurate modal combination methods such as Complete Quadratic Combination, CQC shall be adopted

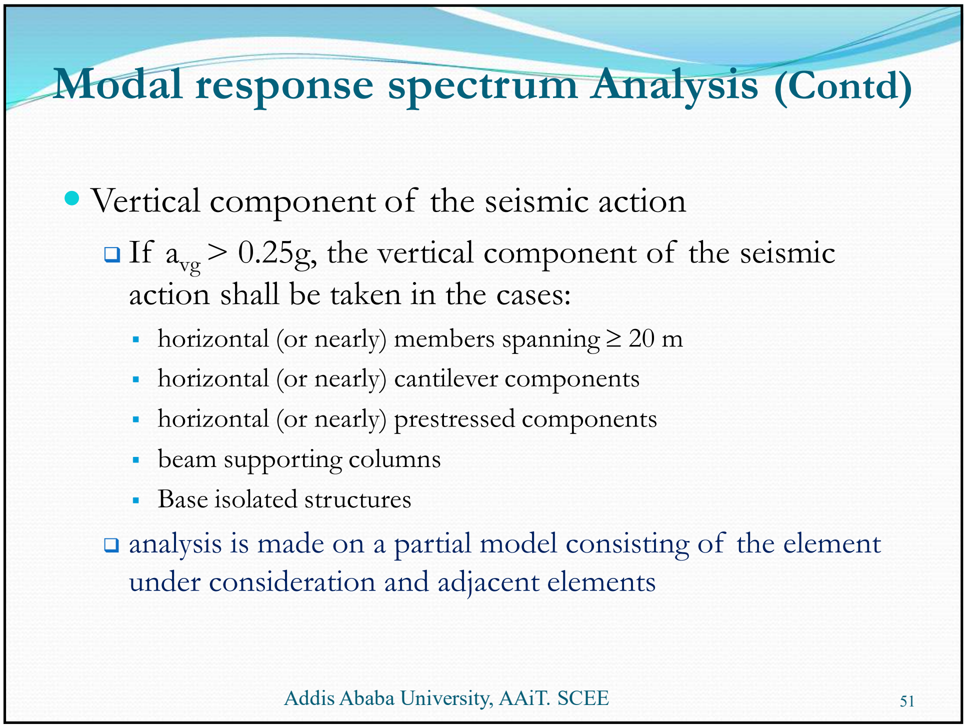
---

Modal response spectrum Analysis (Contd)

- Combination of the effects of seismic action components
  - Horizontal components of the seismic action considered to act simultaneously
    - The maximum value of each action effect due two horizontal components of the seismic action is

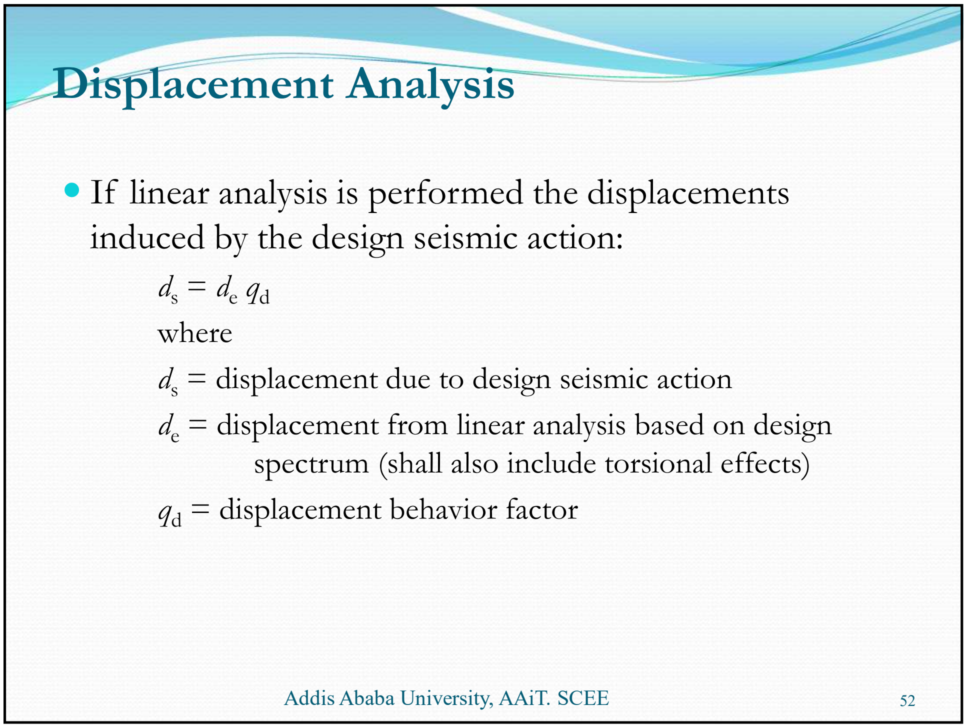
      $\sqrt{E_{Dx}^2 + E_{Dy}^2}$ *or alternatively*

      $E_{Dx} + 0.3E_{Dy}$ *and* $0.3E_{Dx} + E_{Dy}$
    - The sign of each component in the above combination shall be taken as being the most unfavorable of each action effect



Modal response spectrum Analysis (Contd)

- Vertical component of the seismic action
  - ❑ If $a_{vg} > 0.25g$, the vertical component of the seismic action shall be taken in the cases:
    - horizontal (or nearly) members spanning ≥ 20 m
    - horizontal (or nearly) cantilever components
    - horizontal (or nearly) prestressed components
    - beam supporting columns
    - Base isolated structures
  - ❑ analysis is made on a partial model consisting of the element under consideration and adjacent elements



Displacement Analysis

- If linear analysis is performed the displacements induced by the design seismic action:

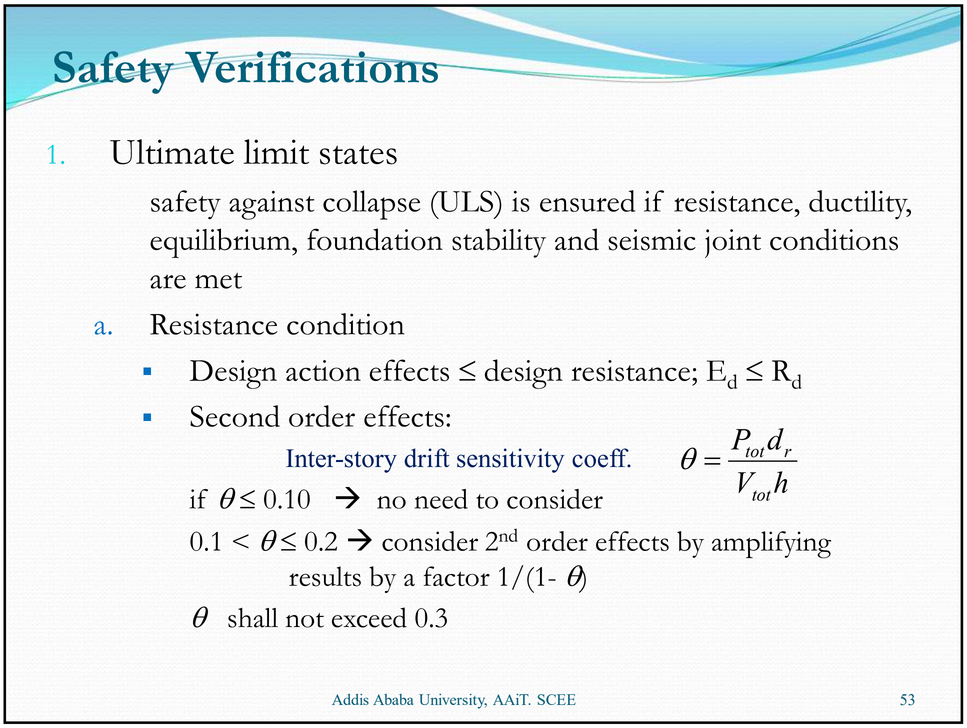
$$d_s = d_e \, q_d$$

where

d_s = displacement due to design seismic action

d_e = displacement from linear analysis based on design spectrum (shall also include torsional effects)

q_d = displacement behavior factor



Safety Verifications

1. Ultimate limit states

   safety against collapse (ULS) is ensured if resistance, ductility, equilibrium, foundation stability and seismic joint conditions are met

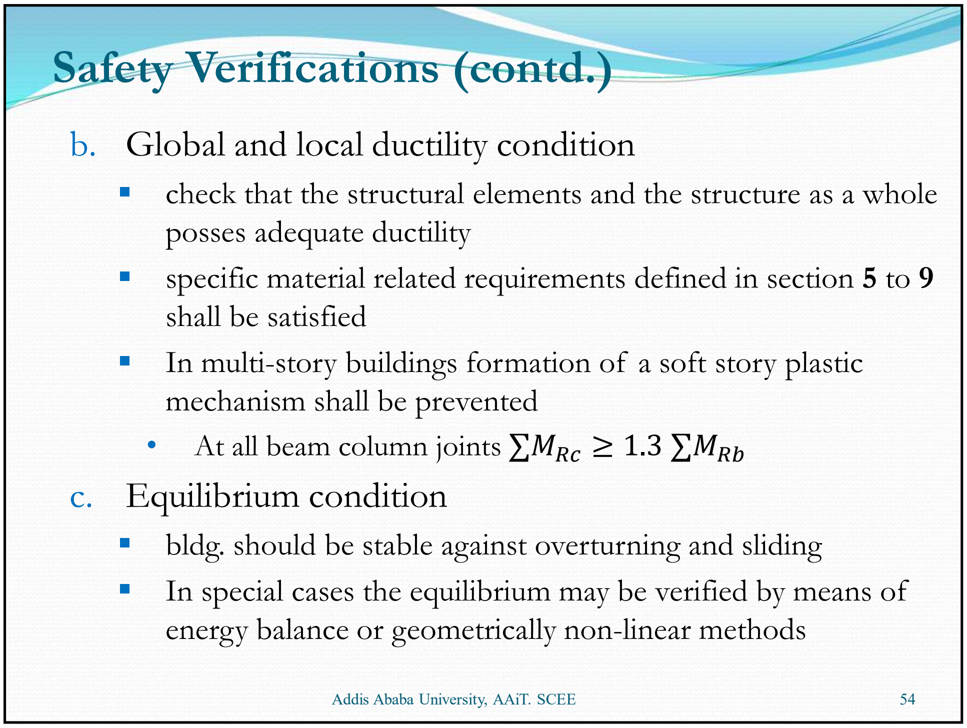
   a. Resistance condition
      - Design action effects ≤ design resistance; $E_d \leq R_d$
      - Second order effects:

        Inter-story drift sensitivity coeff. $\theta = \frac{P_{tot} d_r}{V_{tot} h}$

        if $\theta \leq 0.10$ → no need to consider

        $0.1 < \theta \leq 0.2$ → consider 2nd order effects by amplifying results by a factor $1/(1-\theta)$

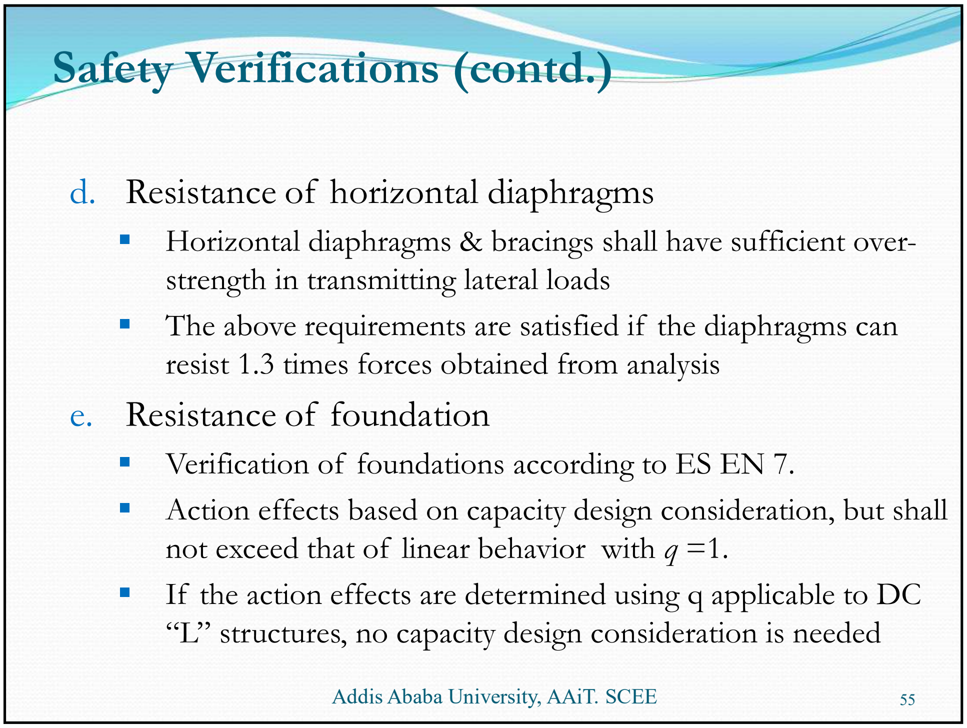
        θ shall not exceed 0.3



Safety Verifications (contd.)

b. Global and local ductility condition
   - check that the structural elements and the structure as a whole posses adequate ductility
   - specific material related requirements defined in section **5** to **9** shall be satisfied
   - In multi-story buildings formation of a soft story plastic mechanism shall be prevented
     - At all beam column joints $\sum M_{Rc} \geq 1.3 \sum M_{Rb}$

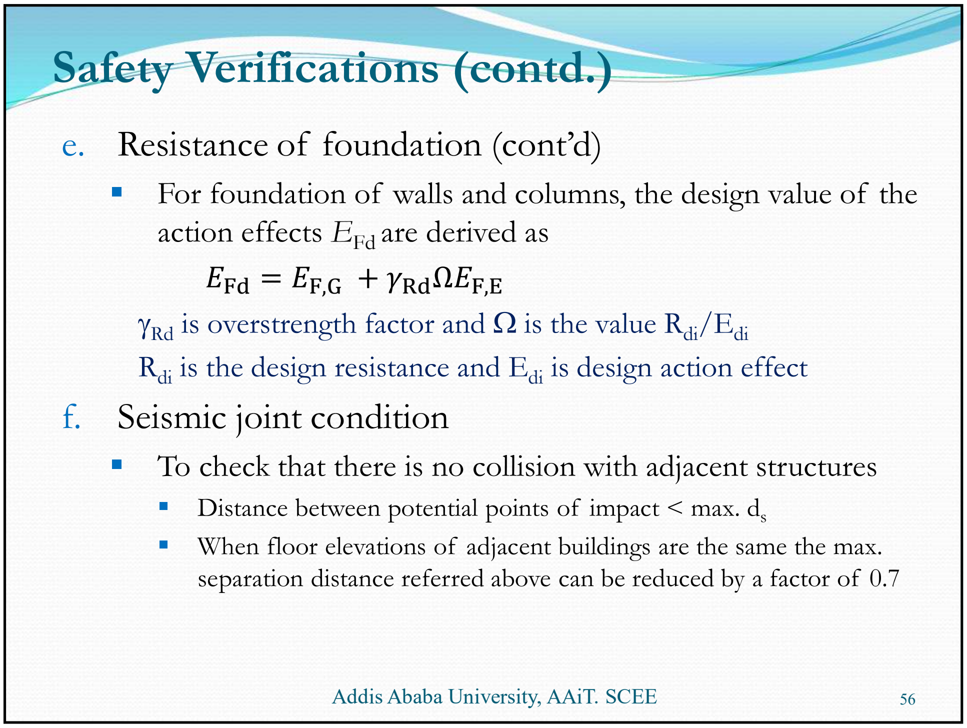
c. Equilibrium condition
   - bldg. should be stable against overturning and sliding
   - In special cases the equilibrium may be verified by means of energy balance or geometrically non-linear methods



Safety Verifications (contd.)

d. Resistance of horizontal diaphragms
   - Horizontal diaphragms & bracings shall have sufficient over-strength in transmitting lateral loads
   - The above requirements are satisfied if the diaphragms can resist 1.3 times forces obtained from analysis

e. Resistance of foundation
   - Verification of foundations according to ES EN 7.
   - Action effects based on capacity design consideration, but shall not exceed that of linear behavior with q =1.
   - If the action effects are determined using q applicable to DC “L” structures, no capacity design consideration is needed



Safety Verifications (contd.)

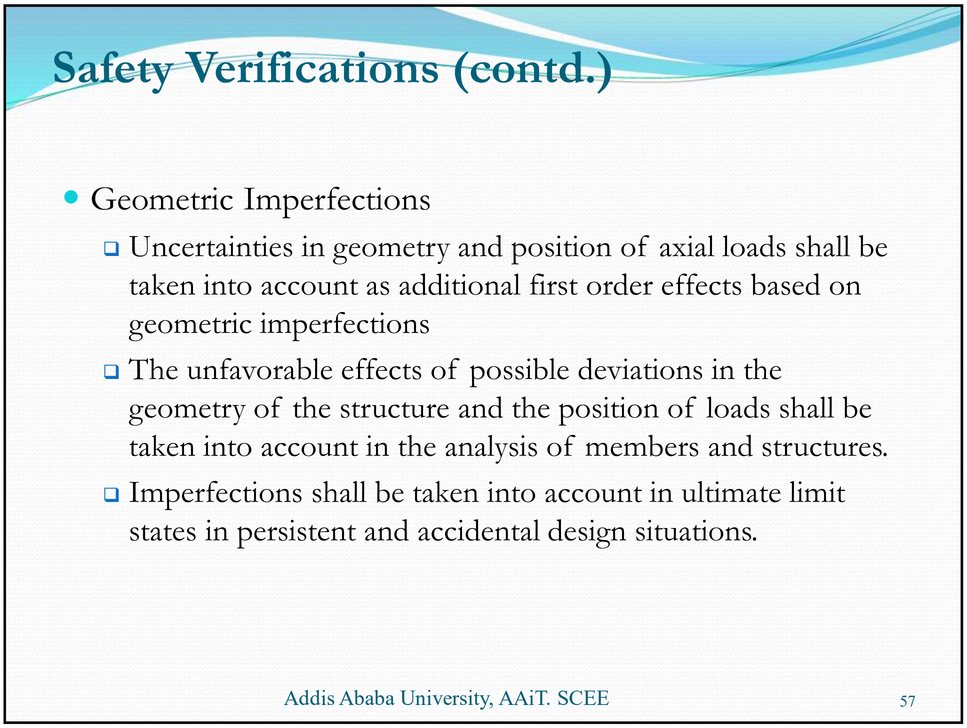
e. Resistance of foundation (cont’d)
   - For foundation of walls and columns, the design value of the action effects E_{Fd} are derived as

$$E_{\mathrm{Fd}} = E_{\mathrm{F,G}} + \gamma_{\mathrm{Rd}}\Omega E_{\mathrm{F,E}}$$

γ_{Rd} is overstrength factor and Ω is the value R_{di}/E_{di}

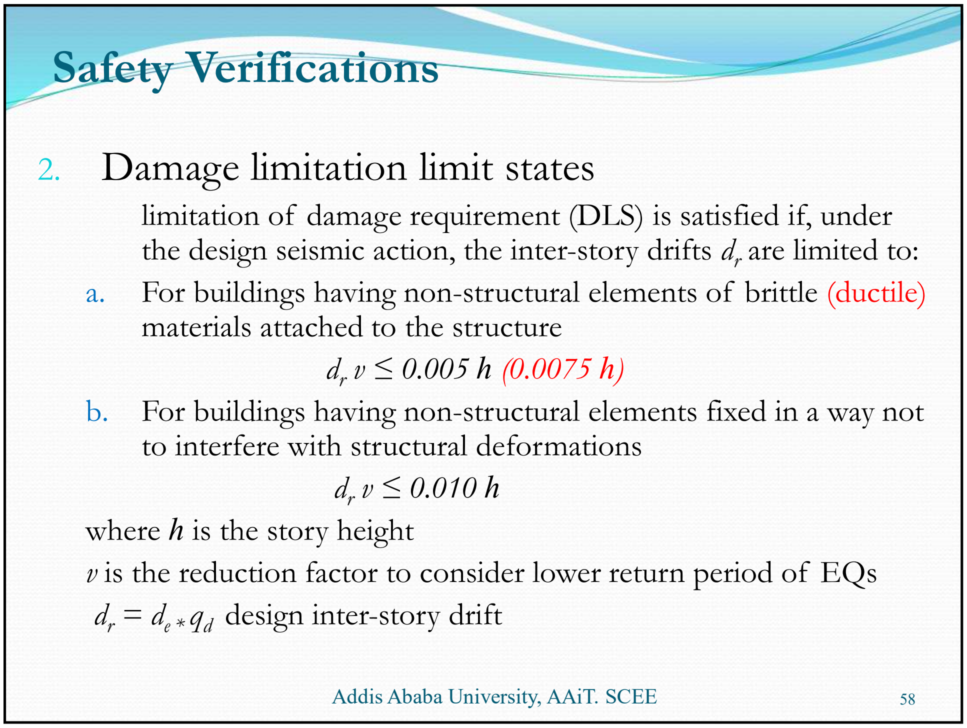
R_{di} is the design resistance and E_{di} is design action effect

f. Seismic joint condition
   - To check that there is no collision with adjacent structures
     - Distance between potential points of impact < max. d_s
     - When floor elevations of adjacent buildings are the same the max. separation distance referred above can be reduced by a factor of 0.7



Safety Verifications (contd.)

- Geometric Imperfections
  - Uncertainties in geometry and position of axial loads shall be taken into account as additional first order effects based on geometric imperfections
  - The unfavorable effects of possible deviations in the geometry of the structure and the position of loads shall be taken into account in the analysis of members and structures.
  - Imperfections shall be taken into account in ultimate limit states in persistent and accidental design situations.



Safety Verifications

2. Damage limitation limit states

limitation of damage requirement (DLS) is satisfied if, under the design seismic action, the inter-story drifts d_r are limited to:

a. For buildings having non-structural elements of brittle (ductile) materials attached to the structure

$$d_r\, v \le 0.005\, h \;(0.0075\, h)$$

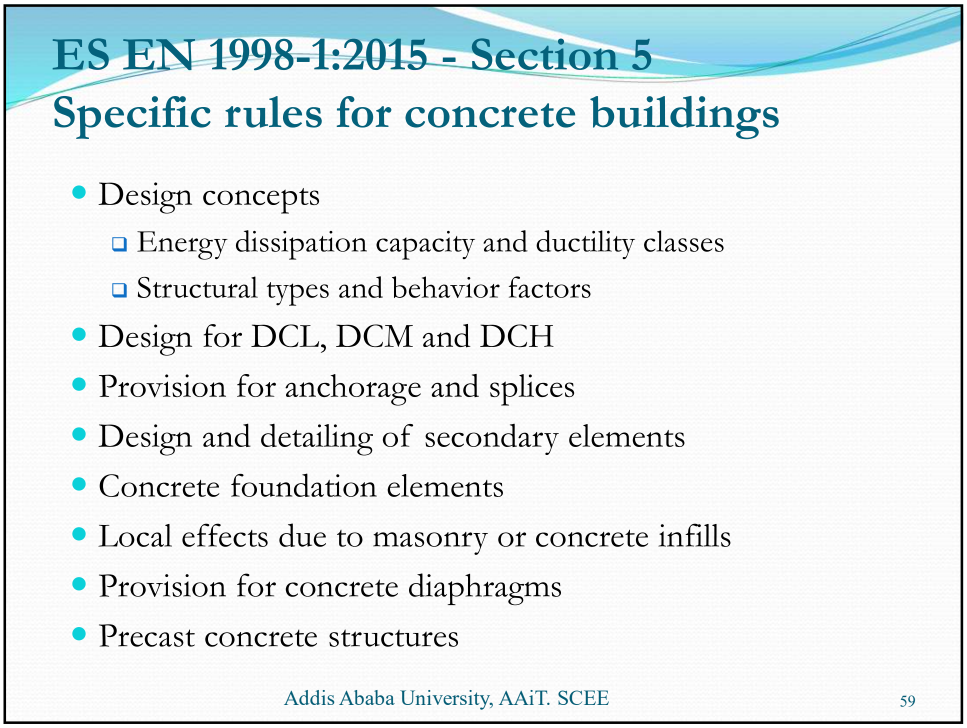
b. For buildings having non-structural elements fixed in a way not to interfere with structural deformations

$$d_r\, v \le 0.010\, h$$

where h is the story height

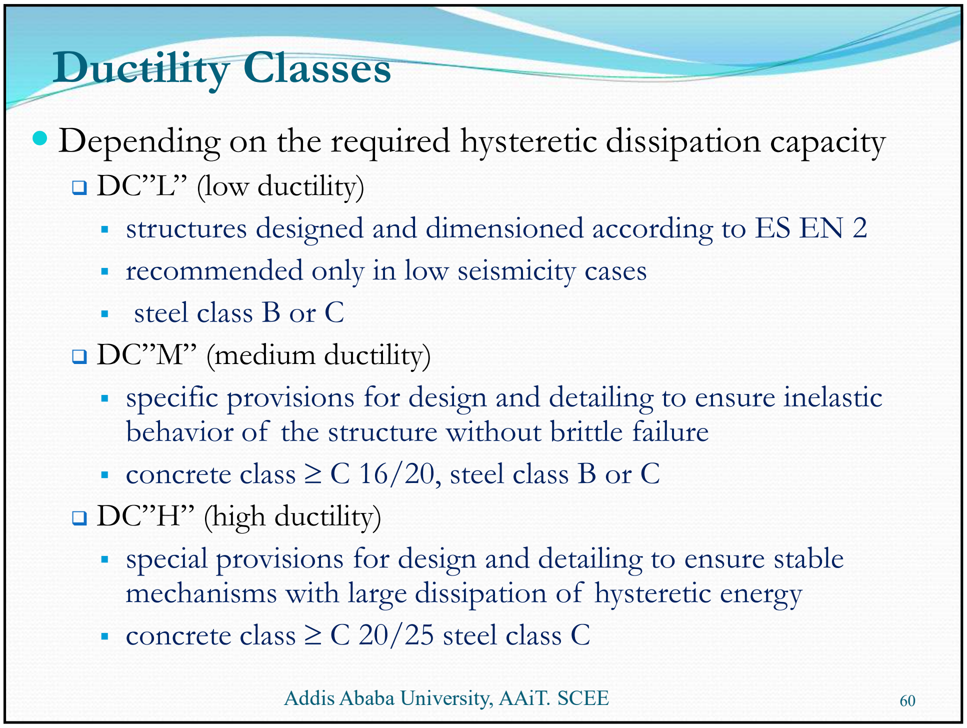
v is the reduction factor to consider lower return period of EQs

$d_r = d_e * q_d$ design inter-story drift



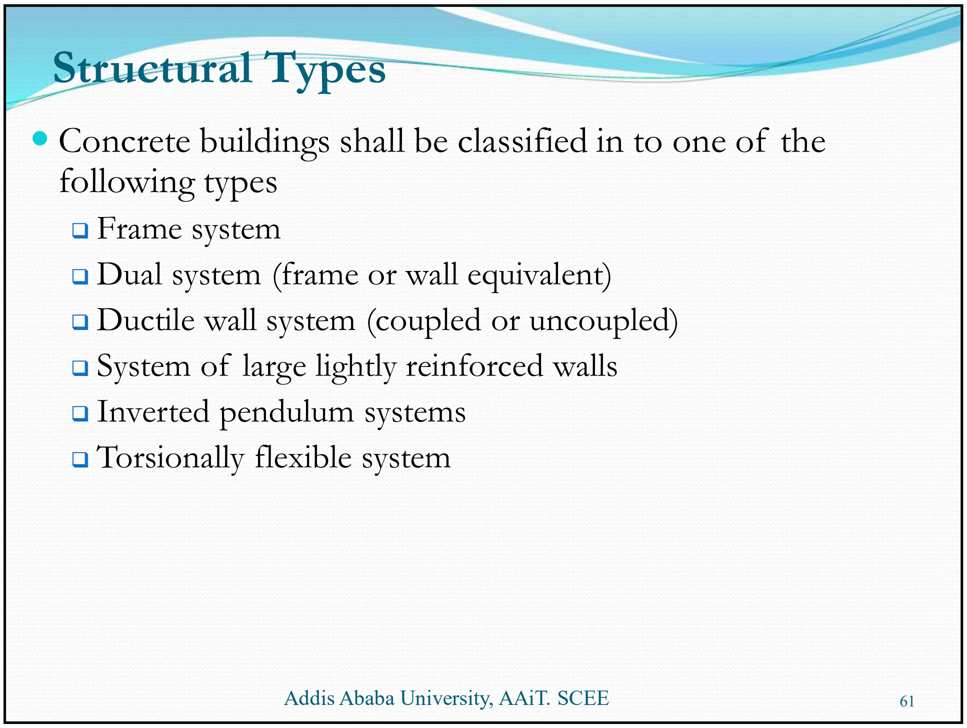
ES EN 1998-1:2015 - Section 5
Specific rules for concrete buildings

- Design concepts
  - Energy dissipation capacity and ductility classes
  - Structural types and behavior factors
- Design for DCL, DCM and DCH
- Provision for anchorage and splices
- Design and detailing of secondary elements
- Concrete foundation elements
- Local effects due to masonry or concrete infills
- Provision for concrete diaphragms
- Precast concrete structures



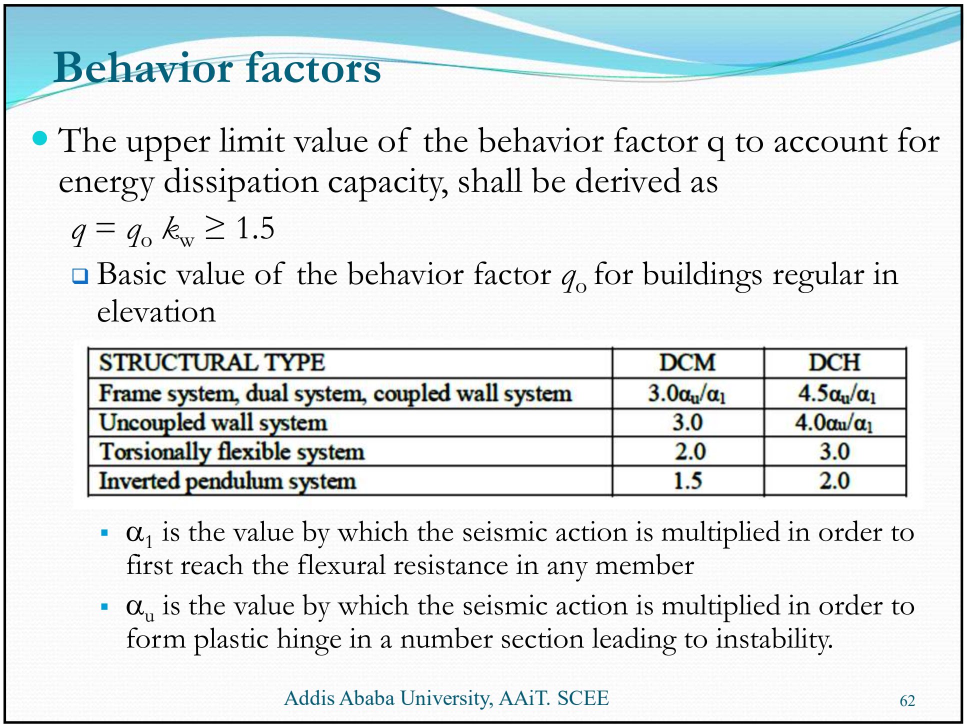
Ductility Classes

- Depending on the required hysteretic dissipation capacity
  - DC"L" (low ductility)
    - structures designed and dimensioned according to ES EN 2
    - recommended only in low seismicity cases
    - steel class B or C
  - DC"M" (medium ductility)
    - specific provisions for design and detailing to ensure inelastic behavior of the structure without brittle failure
    - concrete class ≥ C 16/20, steel class B or C
  - DC"H" (high ductility)
    - special provisions for design and detailing to ensure stable mechanisms with large dissipation of hysteretic energy
    - concrete class ≥ C 20/25 steel class C



Structural Types

- Concrete buildings shall be classified in to one of the following types
  - ❑ Frame system
  - ❑ Dual system (frame or wall equivalent)
  - ❑ Ductile wall system (coupled or uncoupled)
  - ❑ System of large lightly reinforced walls
  - ❑ Inverted pendulum systems
  - ❑ Torsionally flexible system



Behavior factors

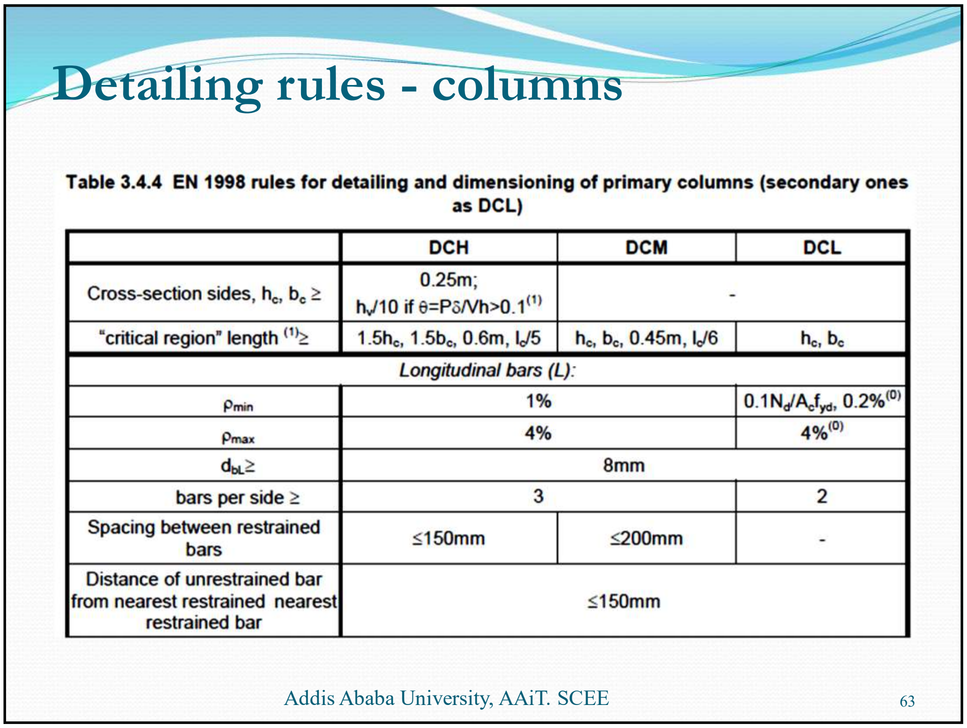
- The upper limit value of the behavior factor q to account for energy dissipation capacity, shall be derived as

  $q = q_o k_w \geq 1.5$

  - ❑ Basic value of the behavior factor q_o for buildings regular in elevation

STRUCTURAL TYPE	DCM	DCH
Frame system, dual system, coupled wall system	$3.0\alpha_u/\alpha_1$	$4.5\alpha_u/\alpha_1$
Uncoupled wall system	3.0	$4.0\alpha_u/\alpha_1$
Torsionally flexible system	2.0	3.0
Inverted pendulum system	1.5	2.0

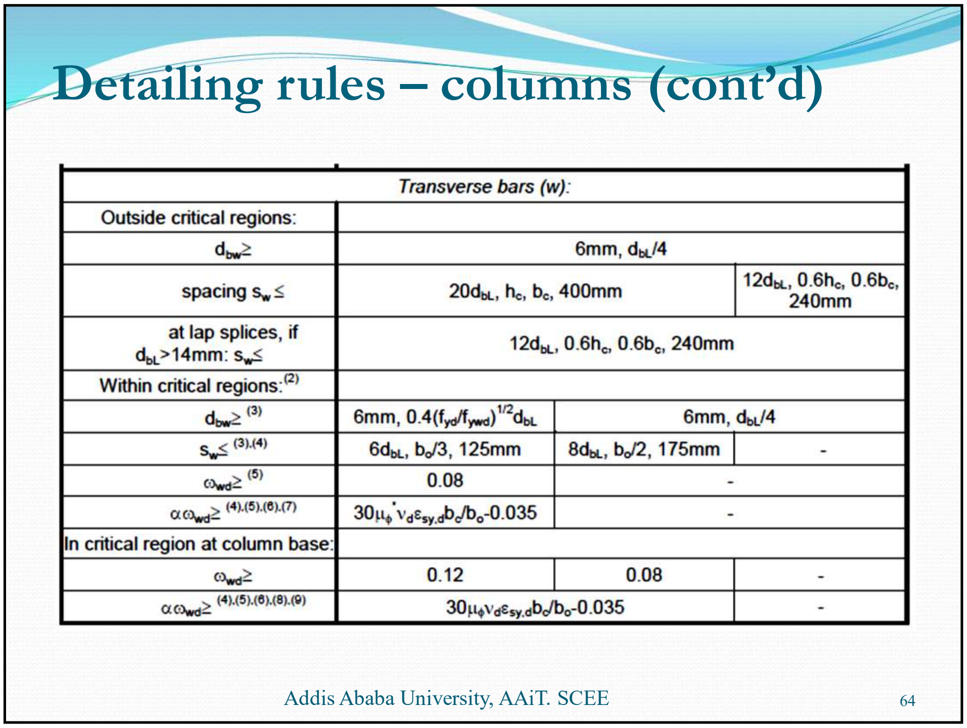
  - α_1 is the value by which the seismic action is multiplied in order to first reach the flexural resistance in any member
  - α_u is the value by which the seismic action is multiplied in order to form plastic hinge in a number section leading to instability.



Detailing rules - columns

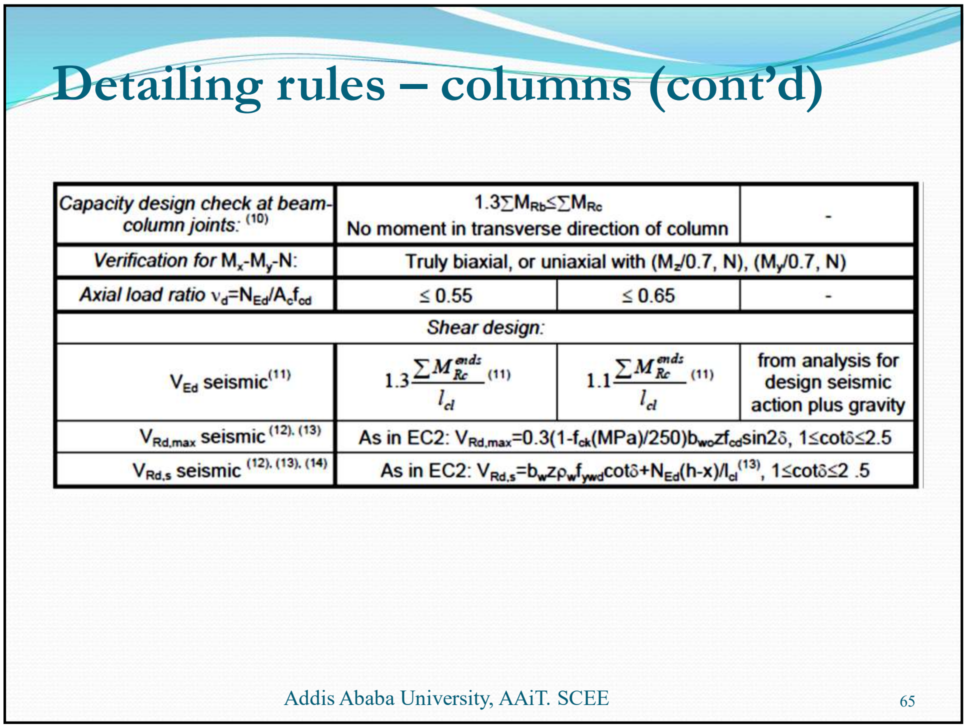
Table 3.4.4 EN 1998 rules for detailing and dimensioning of primary columns (secondary ones as DCL)

	DCH	DCM	DCL
Cross-section sides, h_c, $b_c \geq$	0.25m; $h_v/10$ if $\theta=P\delta/Vh>0.1^{(1)}$	-	
"critical region" length $^{(1)}\geq$	$1.5h_c$, $1.5b_c$, 0.6m, $l_c/5$	h_c, b_c, 0.45m, $l_c/6$	h_c, b_c
Longitudinal bars (L):			
ρ_{min}	1%		$0.1N_d/A_cf_{yd}$, $0.2\%^{(0)}$
ρ_{max}	4%		$4\%^{(0)}$
$d_{bL}\geq$	8mm		
bars per side $\geq$	3		2
Spacing between restrained bars	≤150mm	≤200mm	-
Distance of unrestrained bar from nearest restrained nearest restrained bar	≤150mm		



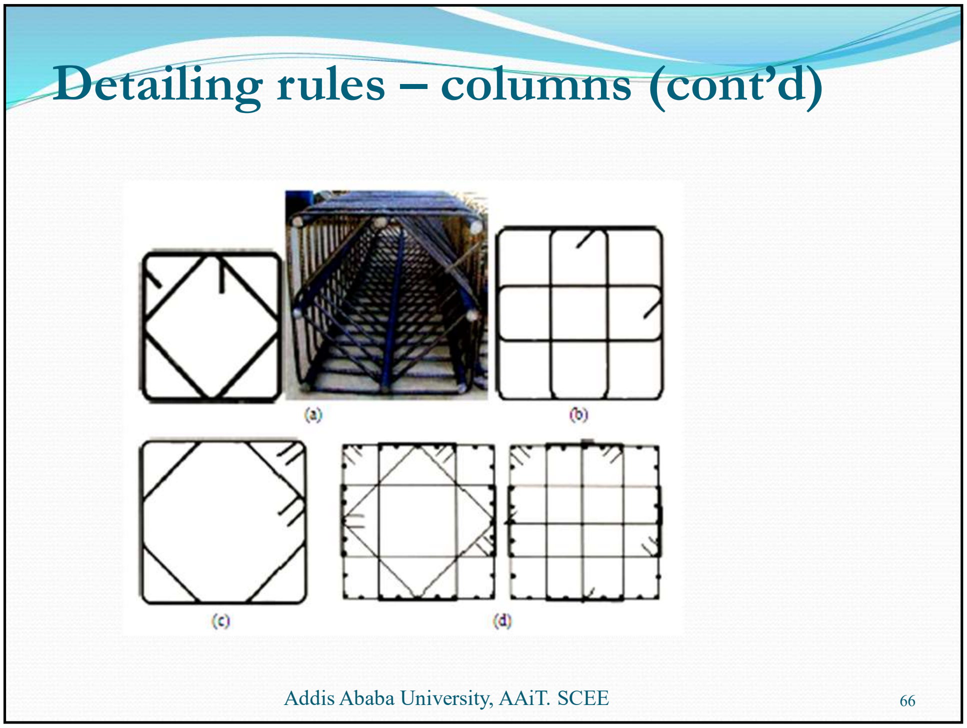
Detailing rules – columns (cont'd)

	DCH	DCM	DCL
Transverse bars (w):			
Outside critical regions:			
$d_{bw}\geq$	6mm, $d_{bL}/4$		
spacing $s_w \leq$	$20d_{bL}$, h_c, b_c, 400mm		$12d_{bL}$, $0.6h_c$, $0.6b_c$, 240mm
at lap splices, if $d_{bL}>14$mm: $s_w\leq$	$12d_{bL}$, $0.6h_c$, $0.6b_c$, 240mm		
Within critical regions:$^{(2)}$			
$d_{bw}\geq$ $^{(3)}$	6mm, $0.4(f_{yd}/f_{ywd})^{1/2}d_{bL}$	6mm, $d_{bL}/4$	
$s_w\leq$ $^{(3),(4)}$	$6d_{bL}$, $b_o/3$, 125mm	$8d_{bL}$, $b_o/2$, 175mm	-
$\omega_{wd}\geq$ $^{(5)}$	0.08	-	
$\alpha\omega_{wd}\geq$ $^{(4),(5),(6),(7)}$	$30\mu_\phi{}^{*}\nu_d\varepsilon_{sy,d}b_c/b_o$-0.035	-	
In critical region at column base:			
$\omega_{wd}\geq$	0.12	0.08	-
$\alpha\omega_{wd}\geq$ $^{(4),(5),(6),(8),(9)}$	$30\mu_\phi\nu_d\varepsilon_{sy,d}b_c/b_o$-0.035		-



Detailing rules – columns (cont'd)

Capacity design check at beam-column joints: (10)	$1.3\sum M_{Rb} \leq \sum M_{Rc}$ No moment in transverse direction of column		-
Verification for M_x-M_y-N:	Truly biaxial, or uniaxial with (M_z/0.7, N), (M_y/0.7, N)		
Axial load ratio $\nu_d = N_{Ed}/A_c f_{cd}$	≤ 0.55	≤ 0.65	-
Shear design:			
V_{Ed} seismic(11)	$1.3\frac{\sum M_{Rc}^{ends}}{l_{cl}}$ (11)	$1.1\frac{\sum M_{Rc}^{ends}}{l_{cl}}$ (11)	from analysis for design seismic action plus gravity
$V_{Rd,max}$ seismic (12), (13)	As in EC2: $V_{Rd,max}=0.3(1-f_{ck}(MPa)/250)b_{wo}zf_{cd}\sin 2\delta$, $1 \leq \cot\delta \leq 2.5$		
$V_{Rd,s}$ seismic (12), (13), (14)	As in EC2: $V_{Rd,s}=b_w z \rho_w f_{ywd}\cot\delta + N_{Ed}(h-x)/l_{cl}$ (13), $1 \leq \cot\delta \leq 2 .5$		



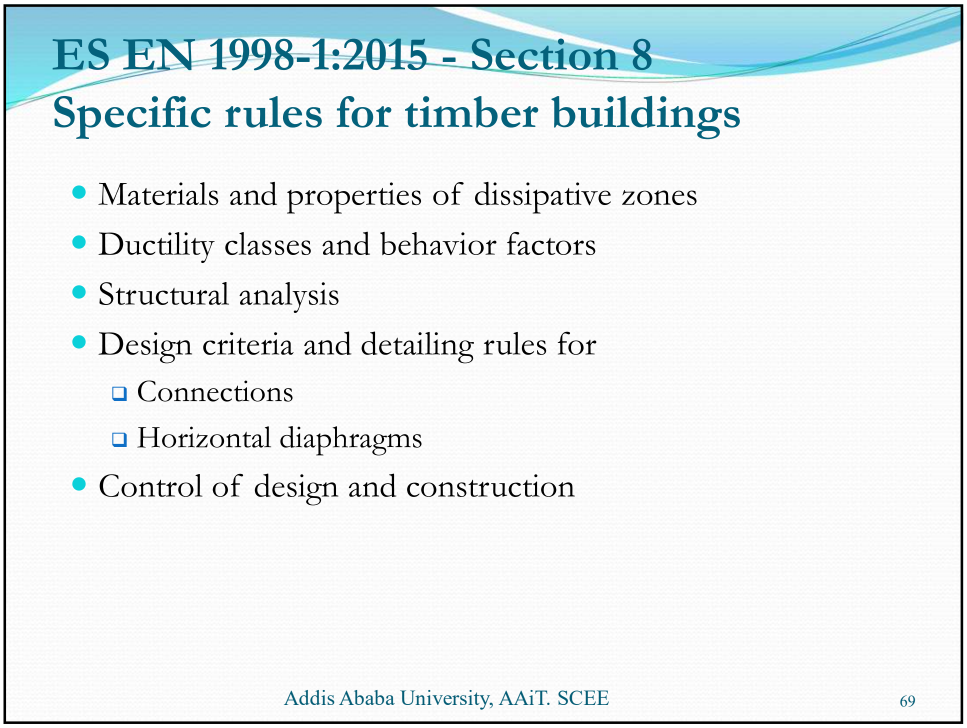
Detailing rules – columns (cont'd)

ES EN 1998-1:2015 - Section 6
Specific rules for steel buildings

- Materials
- Structural types and behavior factors
- Structural analysis
- Design criteria and detailing rules for
    - ❑ Moment Resisting Frames
    - ❑ Concentric Braced Frames
    - ❑ Eccentric Braced frames
- Design rule for inverted pendulum structure
- Design rules for steel structure with concrete core
- Control of design and construction

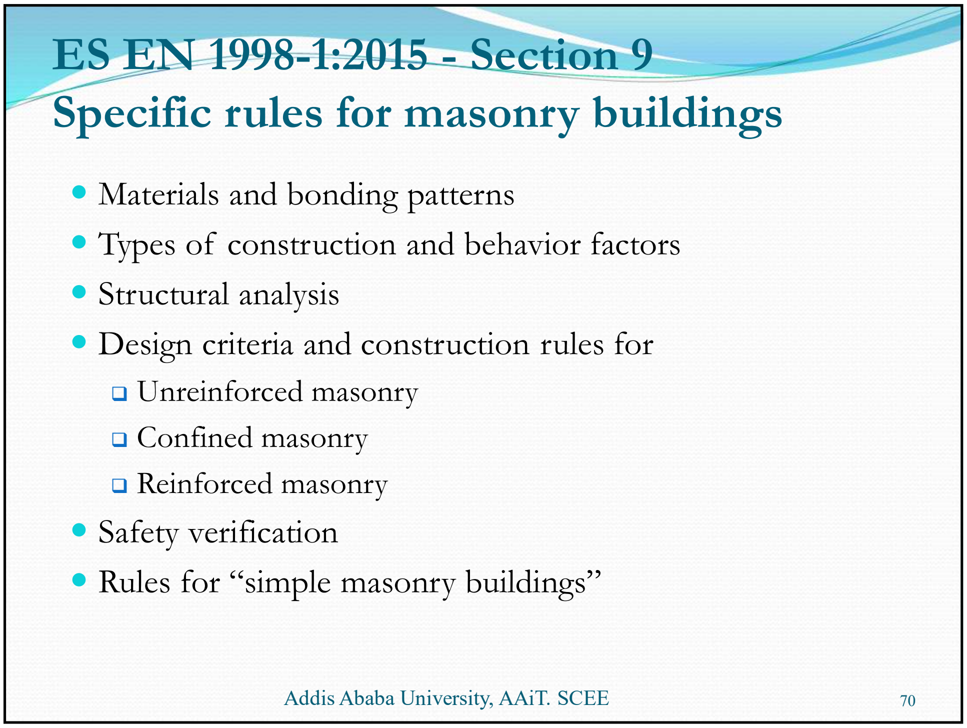
ES EN 1998-1:2015 - Section 7
Specific rules for Composite buildings

- Materials
- Structural types and behavior factors
- Structural analysis
- Design criteria and detailing rules for
    - ❑ Moment Resisting Frames
    - ❑ Concentric Braced Frames
    - ❑ Eccentric Braced frames
- Design and detailing rules for structure made of RC shear wall composite with structural steel elements
- Design and detailing rules for composite steel plate shear walls
- Control of design and construction



ES EN 1998-1:2015 - Section 8
Specific rules for timber buildings

- Materials and properties of dissipative zones
- Ductility classes and behavior factors
- Structural analysis
- Design criteria and detailing rules for
  - ❑ Connections
  - ❑ Horizontal diaphragms
- Control of design and construction



ES EN 1998-1:2015 - Section 9
Specific rules for masonry buildings

- Materials and bonding patterns
- Types of construction and behavior factors
- Structural analysis
- Design criteria and construction rules for
  - ❑ Unreinforced masonry
  - ❑ Confined masonry
  - ❑ Reinforced masonry
- Safety verification
- Rules for "simple masonry buildings"

ES EN 1998-1:2015 - Section 10 Base Isolation

- Fundamental requirements
- Compliance criteria
- General design provisions
- Seismic action
- Behavior factor
- Properties of the isolation system
- Structural analysis
- Safety verification at ultimate limit states

ES EN 1998-1:2015 - Annexes

A. Elastic displacement response spectrum
B. Determination of the target displacement for non linear static analysis
C. Design of the slab of steel-concrete composite beams at beam column joints in moment resisting frames
D. Probabilistic seismic hazard assessment of the horn of Africa region for 10% probability of exceedance in 50 years.

Uniform Building Code, UBC 94 and UBC 97

UBC 94 permits static analysis for:

- structures in zone 1 & 2 with standard occupancy category IV (regular and irregular)
- regular structures under 73 m
- irregular structures ≤ 5 storeys or 20 m.
- structures (regular & irregular) having $T_n < 0.7$ and not located on soil profile S_4
- structures with flexible upper portion (e.g. towers) supported on rigid lower portion, provided that:
  - ❑ both portions are regular
  - ❑ avg. stiffness of lower portion is at least 10 times that of the upper portion
  - ❑ period of entire structure ≤ 1.1 times period upper portion

Irregularities according to UBC 94

- Buildings with irregular shape, change in mass from floor to floor, variable stiffness with height, and unusual setbacks, although aesthetically appealing unfortunately do not perform well in during EQs. UBC requires all irregular buildings with few exceptions use dynamic analysis.
- If a static analysis shows that the storey drifts are substantially linear, then the building can be categorized as vertically regular. Thus it is the drift that determines vertical irregularity, not the plan view.

Irregularities according to UBC 94 (cont'd.)

- Vertical irregularities
  - ❑ a soft storey has stiffness < 70% of the story immediately above, or < 80% avg stiffness of 3 storeys above
  - ❑ a storey has mass irregularity when its mass is > 150% of the mass of a storey above or below (excluding roofs)
  - ❑ a storey has vertical geometric irregularity when the horizontal dimension of a storey's lateral force-resisting system is > 130% of that in an adjacent storey
  - ❑ an in-plane discontinuity exists at a storey when there is an in-plane offset of the load resisting element > the length of those elements
  - ❑ a weak storey is a storey with storey strength < 80% of the storey above

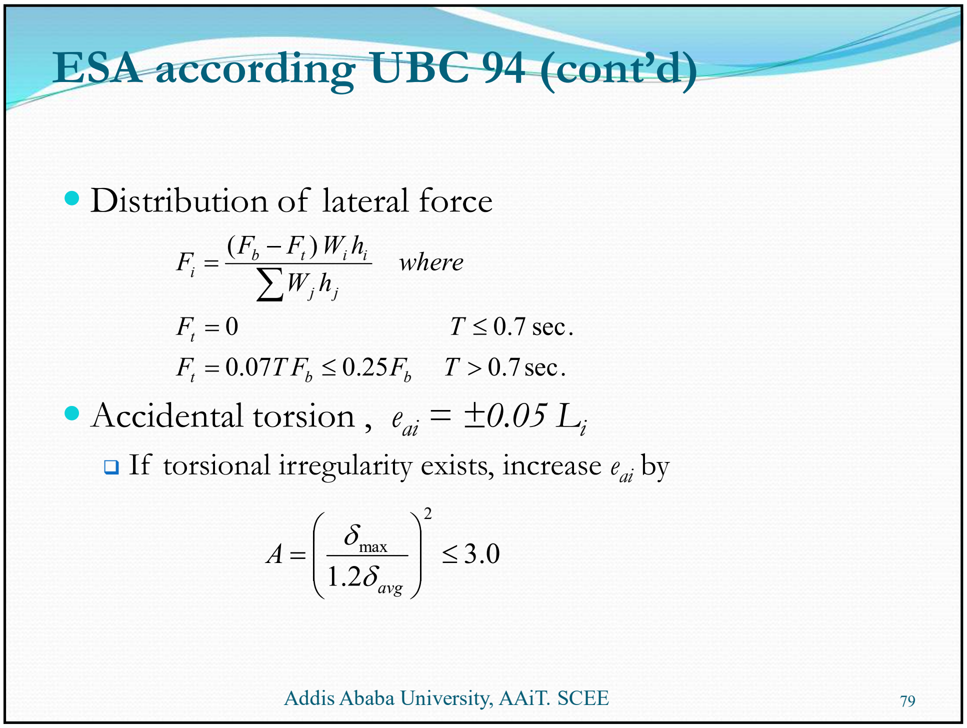
Irregularities according to UBC 94 (contd.)

- Plan irregularities
  - torsional irregularity exists when the max. storey at one end is > 1.2 times avg. storey drifts from both ends
  - a bldg has re-entrant corner irregularity when one or more parts of the structure projects > 15% of the plan dimension
  - diaphragm discontinuity occurs with diaphragms having abrupt discontinuity or variation of stiffness, including cutout or open areas > 50% of the gross diaphragm area, or when stiffness of diaphragm changes > 50% between adj. storeys
  - an out-of-plane offset is a discontinuity in the lateral force path, an out-of-plane offset of vertical elements
  - a non-parallel system is one for which the vertical load-carrying elements are not parallel to or symmetrical about the major orthogonal axes of the lateral force resisting systems

ESA according UBC 94

- Base shear $V = (ZIC/R_w)W$
  - Seismic Zone factor
    - $Z = 0.075, 0.15, 0.20, 0.30$, or 0.40

      (475 yrs return period or 10% probability in 50 yrs)
  - Importance factor
    - $I = 1.25$ for essential and hazardous facilities
    - $I = 1.0$ for all other structures
  - Site coefficient $C = 1.25\, S/T^{2/3} \leq 2.75$
    - $S = 1.0, 1.2, 1.5$ or 2.0
    - $T = C_1 H^{3/4}$ or Rayleigh's formula
  - Structural system coefficient
    - R_w = between 4 to12



ESA according UBC 94 (cont'd)

- Distribution of lateral force

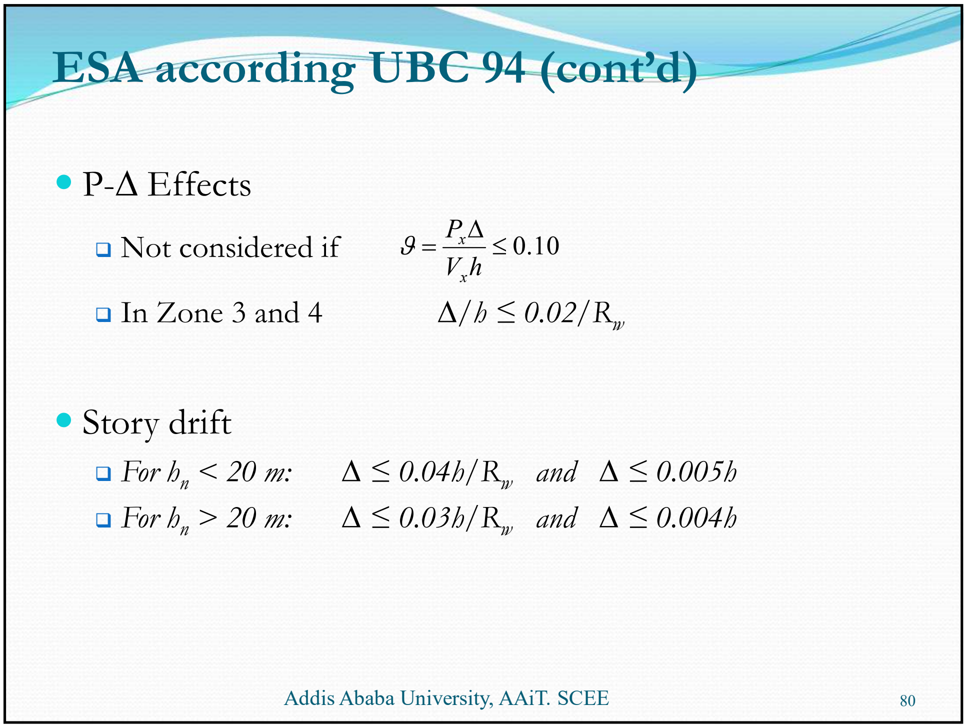
$$F_i = \frac{(F_b - F_t)\,W_i h_i}{\sum W_j h_j} \quad where$$

$$F_t = 0 \qquad\qquad T \le 0.7\ \text{sec.}$$

$$F_t = 0.07\,T\,F_b \le 0.25 F_b \qquad T > 0.7\ \text{sec.}$$

- Accidental torsion , $e_{ai} = \pm 0.05\ L_i$
  - If torsional irregularity exists, increase e_{ai} by

$$A = \left(\frac{\delta_{\max}}{1.2\,\delta_{avg}}\right)^2 \le 3.0$$



ESA according UBC 94 (cont'd)

- P-Δ Effects
  - Not considered if $\vartheta = \frac{P_x \Delta}{V_x h} \le 0.10$
  - In Zone 3 and 4 $\Delta/h \le 0.02/R_w$

- Story drift
  - For $h_n < 20$ m: $\Delta \le 0.04h/R_w$ and $\Delta \le 0.005h$
  - For $h_n > 20$ m: $\Delta \le 0.03h/R_w$ and $\Delta \le 0.004h$

ESA according UBC 97

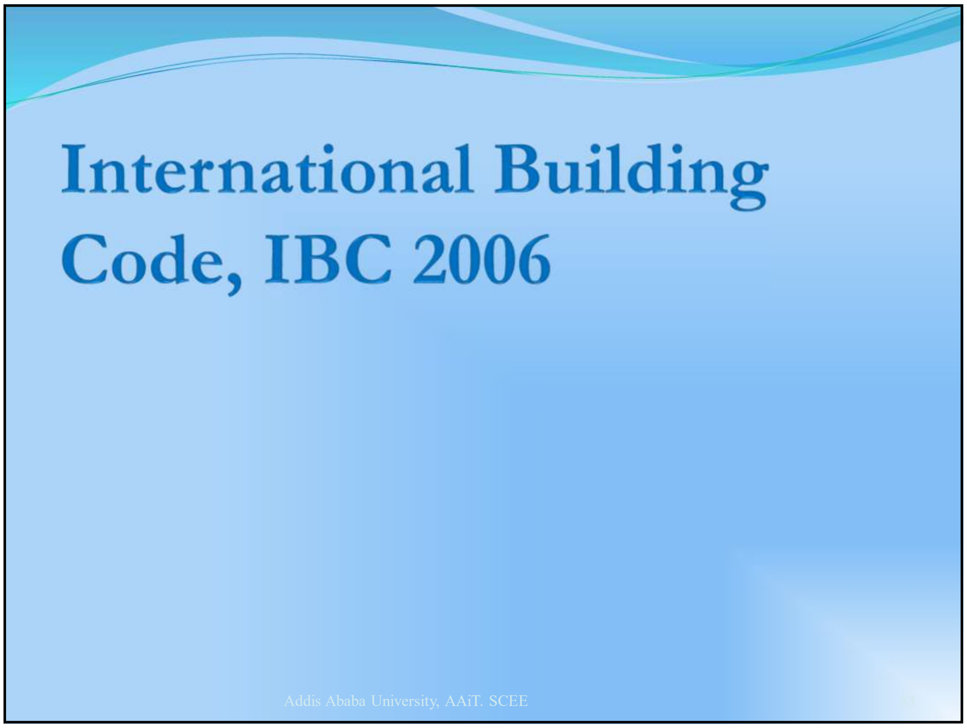
- **Design Base shear**
- The total design base shear in a given direction shall be determined from: $V = \frac{C_v}{R}\frac{I}{T}W$
- The total design base shear need not exceed: $V = \frac{2.5 C_a I}{R}W$
-
- The total design base shear shall not be less than: $V = 0.11 C_a I W$
- In addition, for Seismic Zone 4, the total base shear shall also not be less than: $V = \frac{0.8 Z C_v I}{R}W$
- C_v and C_a (velocity and acceleration related coefficients) account for both seismicity of the site and soil effect of 6 soil types.

R ranges from 2.2 to 8.5

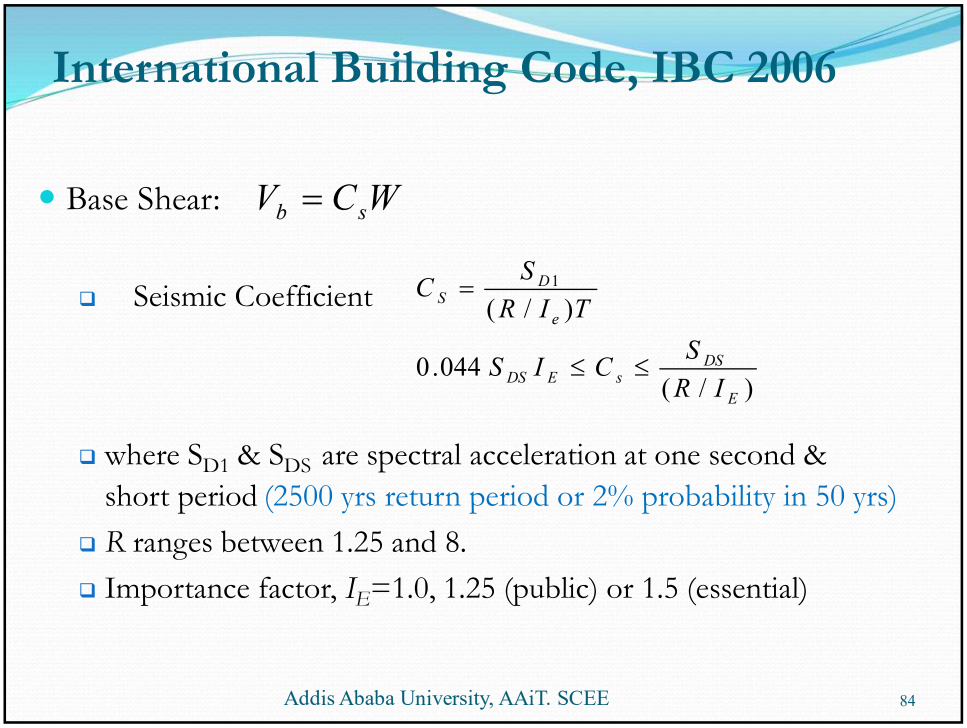
ESA according UBC 97 (cont'd)

- Major differences between UBC 94 and UBC 97
  - ❑ R values reduced from 4 – 12 to 2.2 – 8.5
  - ❑ Site coefficient $C = 1.25\ S/T \leq 2.5$
    - Site coefficient formula $1/T^{2/3}$ changed to $1/T$
    - Upper bound of spectra reduced from 2.75 to 2.5
  - ❑ Soil classes from 4 soil types to 6 soil types
  - ❑ Story drift limitation
    - For $h_n < 20$ m: $\Delta \leq 0.04h/R_w$ and $\Delta \leq 0.005h$
    - For $h_n > 20$ m: $\Delta \leq 0.03h/R_w$ and $\Delta \leq 0.004h$
  - ❑ Changed to
    - For $T < 0.7$ s: $\Delta_m \leq 0.025h$
    - For $T \geq 0.7$ s: $\Delta_m < 0.020h$

Where $\Delta_m = 0.7R\,\Delta_s$



International Building Code, IBC 2006



International Building Code, IBC 2006

- Base Shear: $V_b = C_s W$
  - Seismic Coefficient $C_S = \dfrac{S_{D1}}{(R/I_e)T}$

$$0.044\, S_{DS} I_E \leq C_s \leq \frac{S_{DS}}{(R/I_E)}$$

  - where S_{D1} & S_{DS} are spectral acceleration at one second & short period (2500 yrs return period or 2% probability in 50 yrs)
  - R ranges between 1.25 and 8.
  - Importance factor, I_E=1.0, 1.25 (public) or 1.5 (essential)

International Building Code, IBC 2006

- Fundamental period estimation

$$T_1 = C_t \, h_n^x$$

Where C_t and x are defined as:

Structure type	C_t	x
Steel moment resisting frames	0.075	0.8
Concrete moment resisting frames	0.05	0.9
Eccentrically braced frames	0.075	0.75
All other structural systems	0.05	0.75

International Building Code, IBC 2006

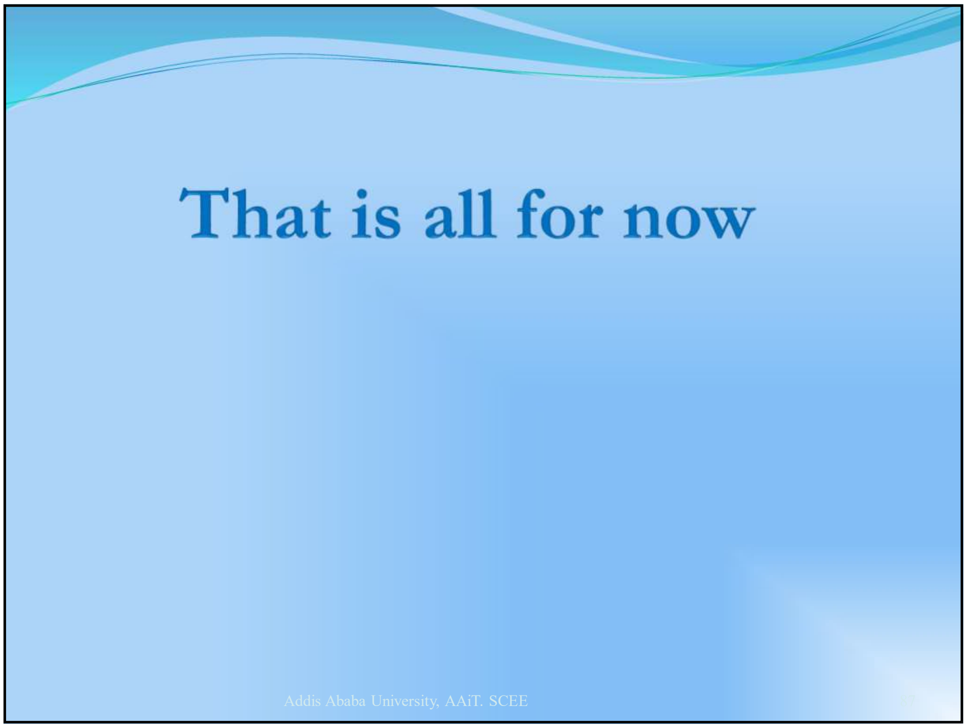
- Lateral force distribution

$$F_j = V_b \frac{w_j h_j^k}{\sum_{i=1}^{N} w_i h_i^k} \qquad \text{where } k = \begin{cases} 1 & T_1 \le 0.5 \\ (T_1 + 1.5)/2 & 0.5 < T_1 < 2.5 \\ 2 & T_1 \ge 2.5 \end{cases}$$

- Story overturning moment

$$M_x = \tau \, \Sigma \, F_i(h_i - h_x)$$

where τ reduction factor for bldgs taller than 10 storeys.



That is all for now