BC3: 2013

Guidebook for Design of Buildings in Singapore to Requirements in SS EN 1998-1

Building and Construction Authority

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Foreword

This "Guidebook for Design of Buildings in Singapore to Requirements in SS EN 1998-1" referred to as BC3: 2013 gives provisions for the structural design against seismic actions and is to be read in conjunction with the Singapore National Annex to SS EN 1998-1: 2012.

Acknowledgement

The Building and Construction Authority of Singapore (BCA) would like to thank the members of the Workgroup formed to develop this Guidebook for their valuable contributions.

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1. General Philosophy

1.1 New buildings that are above 20 metres in height and existing buildings undergoing very major addition or alteration works[A] founded on certain Ground Types shall be checked for an enhanced robustness consideration to cater for impact of Seismic Actions due to distant earthquakes with a probability of exceedance of 10% in 50 years according to the methodology outlined in the flowchart in Figure 1. This requirement will apply to the following types of building and the corresponding Ground Types (determined as per paragraph 2.3):

- Special buildings[B] on Ground Types "C", "D" or "S_1" and
- Ordinary buildings[C] on Ground Types "D" or "S_1"

1.2 As Singapore is in a low seismicity region, Ductility Class Low (DCL)[D] design and detailing can be adopted for reinforced concrete, precast concrete, structural steel or composite buildings.

[A] Very major addition or alteration works refers to:

- addition of floors on existing buildings that results in the building attaining a height greater than 20 metres, or
- structural works affecting key structural elements supporting total tributary area of more than 60% of the total structural floor area of a building of height greater than 20 metres, or
- additions of new structural floor areas of more than 60% of the existing total structural floor area of a building of height greater than 20 metres.

[B] Special buildings refer to hospitals, fire stations, civil defence installations, Government Ministry offices and institutional buildings.

[C] Ordinary buildings are buildings other than those classified as "Special buildings".

[D] DCL steel reinforcement detailing for reinforced concrete structures would follow the requirements of SS EN 1992-1-1 (Design of concrete structures – General rules and rules for buildings) and in conjunction with Clause 5.3.2(1)P of SS EN 1998-1. For buildings of structural steel or composite construction, the element design shall follow the relevant parts of SS EN 1993 (Design of steel structures) or SS EN 1994 (Design of composite structures) respectively.

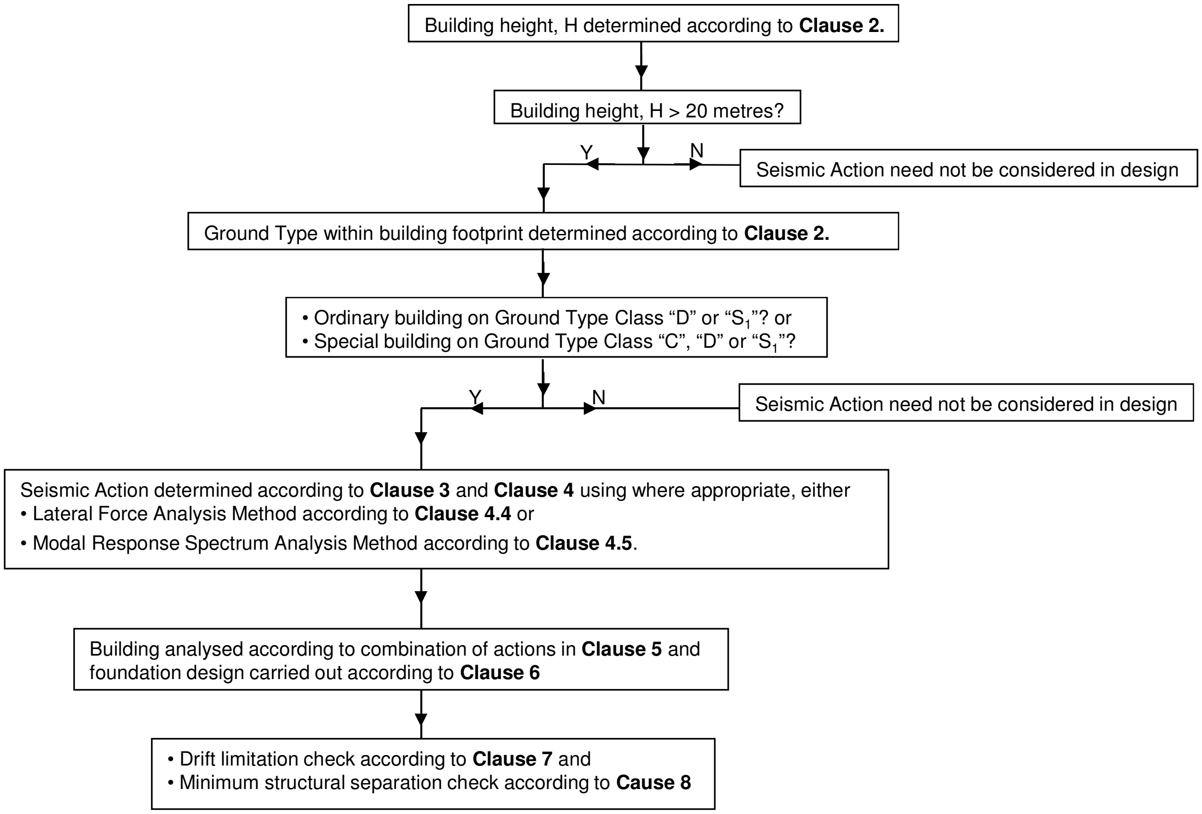


Figure 1 – Flowchart to determine whether enhanced robustness consideration applies

2. Building Height and Ground Type Classification

2.1 The building height, H shall be taken from the foundation or top of a rigid basement to the topmost habitable structural floor level[E], as shown in Figure 2.

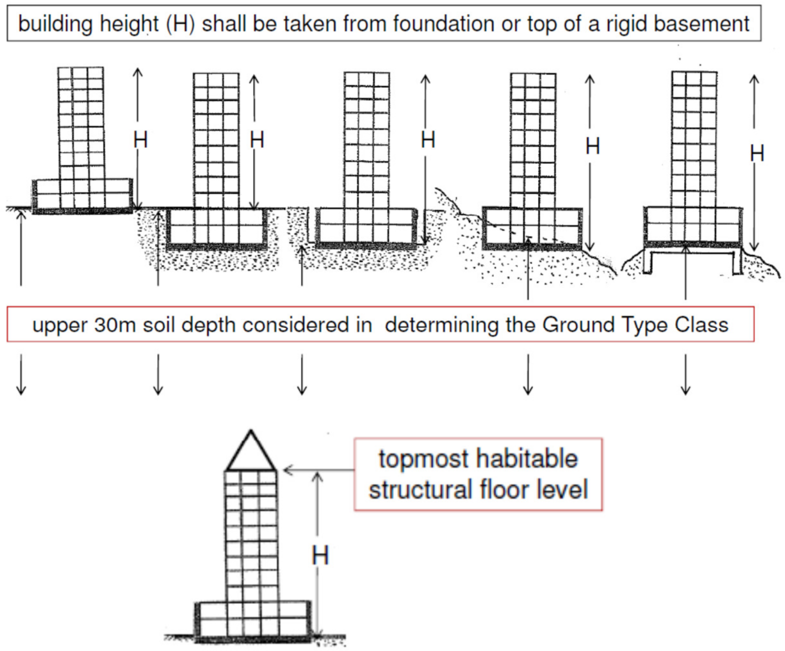


Figure 2 - Example of determination of topmost habitable structural floor level

2.2 The Ground Type within the footprint of structurally independent building[F] shall be determined firstly by computing the value of P using either soil parameter of shear wave velocity ($v_{s,30}$), standard penetration test ($N_{SPT(blows/300mm)}$) or undrained shear strength (c_u) in the upper 30m soil depth as:

$$P = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{P_i}}$$

where $\sum_{i=1}^{n} d_i$ is equal to 30m;
P_i is the soil parameter ($v_{s,30}$, $N_{SPT(blows/300mm)}$ or c_u); and
d_i is the thickness of layer i between 0 and 30m.

[E] Topmost habitable structural floor level refers to topmost floor accessible for usage.

[F] Structurally independent building refers to a building that depends only on the structural framing within its own footprint for stability and resistance against design actions.

2.3 The computed value of P is then used to determine the Ground Type from Table 1 below.

Value of P as computed from paragraph 2.2 for soil in the upper 30m			Ground Type	Description of stratigraphic profile
Shear-Wave Velocity. $v_{s,30}$ (m/s)	**N_{SPT} (blows/30cm)**	**Undrained Shear Strength, c_u (kPa)**		
> 800	Not applicable	Not applicable	**A**	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.
360 - 800	> 50	> 250	**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.
180 - 360	15 - 50	70 - 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	< 15	< 70	**D**	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soils.
< 100	< 5	10 - 20	**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.

Table 1 – Determining Ground Type from computed value of P

2.4 In determining the Ground Type,

(a) the top 30m soil depth is taken from the existing ground level even if the development requires excavations for basement construction;

(b) if more than one of the 3 soil parameters mentioned in table above are available, the most onerous Ground Type determined from these soil parameters shall be adopted;

(c) the most onerous Ground Type shall be adopted if there are different Ground Types spatially distributed as determined from various site investigations within the footprint of a building; and

(d) these rules shall apply regardless of whether the building is founded on piles that extend to hard soil stratum or not.

3. Design Seismic Actions

3.1 The earthquake ground motion in Singapore is represented by the horizontal <u>elastic</u> response spectrum[G], that is defined by parameters given in the National Annex to SS EN 1998-1, an extract of which is reproduced below for ease of reference.

Ground Type	S	T_B (s)	T_C (s)	T_D (s)
C	1.6	0.4	1.1	10.4
D	2.5	0.9	1.6	4.6
S_1	3.2	1.6	2.4	2.4

Note: a_{gR}[H] = 0.175m/s^2

3.2 The horizontal <u>elastic</u> response spectra defined in paragraph 3.1 is presented below as spectral accelerations $S_e(T)$ at 5% structural damping vs. structural period T for Ground Types C, D and S_1, as shown in Figures 3, 4 and 5 respectively. The design response spectrum $S_d(T)$ that can be used as input directly into any conventional structural analysis software is given by:

$$\boldsymbol{S_d(T) = \frac{S_e(T).\gamma_l}{q}}$$

where $S_d(T)$ is the design spectral acceleration at 5% structural damping;

γ_l is the importance factor (refer to paragraph 3.4); and

q is the behaviour factor (refer to paragraph 3.3).

[G] The parameters defining the shape of the horizontal <u>elastic</u> response spectra for different Ground Types can be found in the National Annex to SS EN 1998-1 (under Clause 3.2.2.1(4), 3.2.2.2(1)P).

[H] a_{gR} is the reference peak ground acceleration on type A ground (refer National Annex to SS EN 1998-1 under Clause 3.2.1(1), (2), (3)).

T (sec)	Spectral Acceleration $S_e(T)$ (%g)		T (sec)	Spectral Acceleration $S_e(T)$ (%g)
0.0	2.88		1.8	4.40
0.1	3.96		2.0	3.96
0.2	5.04		2.2	3.60
0.3	6.12		2.4	3.30
0.4	7.20		2.7	2.93
0.5	7.20		3.0	2.64
0.6	7.20		3.5	2.26
0.7	7.20		4.0	1.98
0.8	7.20		4.6	1.72
0.9	7.20		5.2	1.52
1.0	7.20		6.0	1.32
1.1	7.20		7.0	1.13
1.2	6.60		8.0	0.99
1.4	6.09		9.0	0.88
1.6	4.95		10.0	0.79

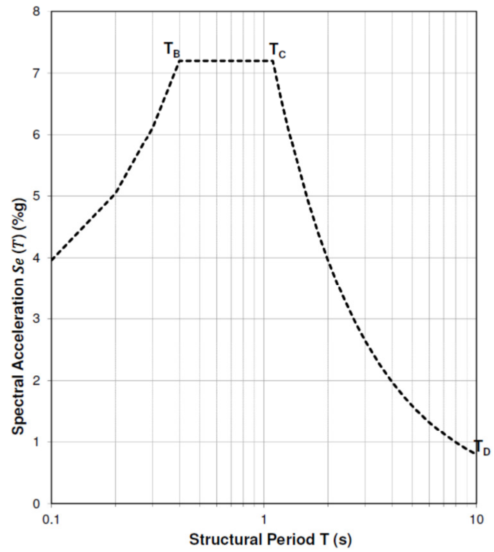


Figure 3 - Spectral accelerations, $S_e(T)$, for **Ground Type C** at 5% structural damping

T (sec)	Spectral Acceleration $S_e(T)$ (%g)		T (sec)	Spectral Acceleration $S_e(T)$ (%g)
0.0	4.50		1.8	10.00
0.1	5.25		2.0	9.00
0.2	6.00		2.2	8.18
0.3	6.75		2.4	7.50
0.4	7.50		2.7	6.67
0.5	8.25		3.0	6.00
0.6	9.00		3.5	5.14
0.7	9.75		4.0	4.50
0.8	10.50		4.6	3.91
0.9	11.25		5.2	3.06
1.0	11.25		6.0	2.30
1.1	11.25		7.0	1.69
1.2	11.25		8.0	1.29
1.4	11.25		9.0	1.02
1.6	11.25		10.0	0.83

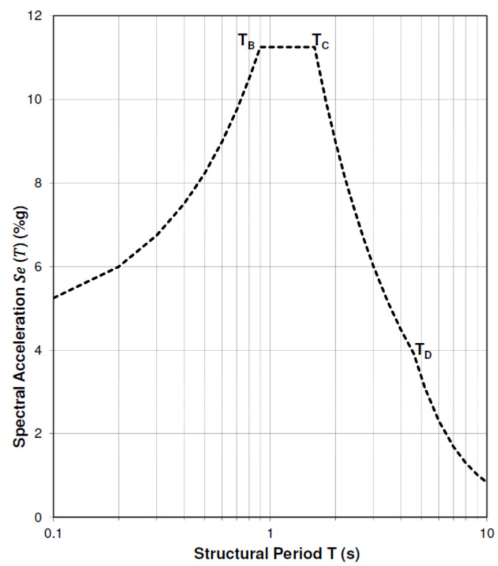


Figure 4 - Spectral accelerations, $S_e(T)$, for **Ground Type D** at 5% structural damping

T (sec)	Spectral Acceleration $S_e(T)$ (%g)		T (sec)	Spectral Acceleration $S_e(T)$ (%g)
0.0	5.76		1.8	14.40
0.1	6.30		2.0	14.40
0.2	6.84		2.2	14.40
0.3	7.38		2.4	14.40
0.4	7.92		2.7	11.38
0.5	8.46		3.0	9.22
0.6	9.00		3.5	6.77
0.7	9.54		4.0	5.18
0.8	10.08		4.6	3.92
0.9	10.62		5.2	3.07
1.0	11.16		6.0	2.30
1.1	11.70		7.0	1.69
1.2	12.24		8.0	1.30
1.4	12.78		9.0	1.02
1.6	14.40		10.0	0.83

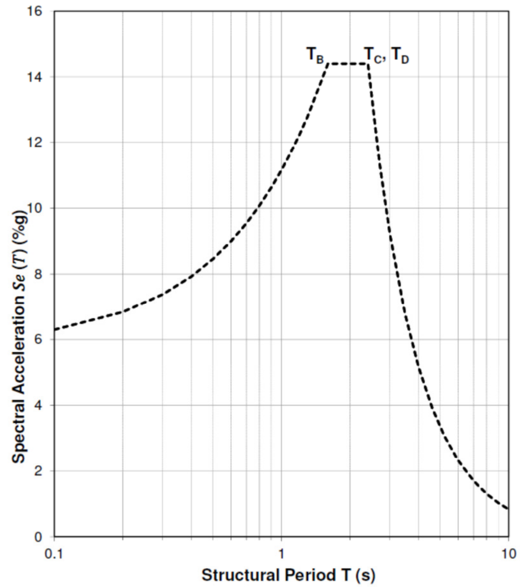


Figure 5 - Spectral accelerations, $S_e(T)$, for **Ground Type S_1** at 5% structural damping

3.3 Determining the behaviour factor q. The q factor depends on the structural system, regularity in elevation and plan, and ductility class. After accounting for any enhancements or reductions as per paragraphs 3.3.1 and 3.3.2, a **minimum value of 1.5 can be adopted for the q factor** in determining the design seismic action **for all building types** (i.e. concrete, steel and composite steel-concrete structures).

3.3.1 Structural regularity. Regularity of the structure (in elevation and in plan) influences the required structural model (planar or spatial), the required method of analysis and the required behaviour factor q (refer to Clause 4.2.3.1 of SS EN 1998-1).

- Regularity in plan[i]. Regularity in plan may influence the magnitude of the seismic action (via the overstrength factor α_u/α_1) (refer to Clauses 5.2.2.2 (5), 6.3.2(3) and 7.3.2(3) of SS EN 1998-1). A conservative approach could be adopted considering the structure as being irregular in plan without taking into account any enhancements provided for the behaviour factor q if a regular structural configuration is adopted. This approach would also require that a spatial rather than a planar model be used for structural analysis.

[i] Refer to Clause 4.2.3.2 of SS EN 1998-1 for the criteria for regularity in plan.

- Regularity in elevation[J]. Regularity in elevation would determine if any reduction to the behaviour factor q is needed. A conservative approach could be adopted considering the structure as being irregular in elevation by applying a 20% reduction to the behaviour factor q (refer to Clause 4.2.3.1(7) of SS EN 1998-1). This approach would also require that the modal response spectrum method be used for structural analysis (refer to paragraph 4 for details on analysis methods).

3.3.2 Ductility Class. As Singapore is in a low seismicity region, Ductility Class Low (DCL)[K] design and detailing can be adopted (refer paragraph 1.2). If Ductility Class Medium (DCM) or Ductility Class High (DCH) design and detailing is adopted, an appropriate limiting behaviour factor q shall be used and other associated requirements in SS EN 1998-1 and other relevant parts of BS EN 1998, where applicable, shall be adhered to.

3.4 An importance factor γ_I. An Importance factor γ_I of 1.4 or 1.0 shall be applied when deriving the design response spectrum for Special or Ordinary buildings respectively.

[J] Refer to Clause 4.2.3.3 of SS EN 1998-1 for the criteria for regularity in elevation.

[K] for DCL Ductility Class, the upper limit of the reference value of the behaviour factor q shall be 1.5 for concrete buildings and 2.0 for steel & composite steel-concrete buildings. Appropriate enhancements or reductions shall be applied to this reference value based on structural regularity considerations (refer to paragraph 3.3).

4. Analysis Methods

4.1 An appropriate analysis method (lateral force method or modal response spectrum method) shall be adopted (refer to paragraph 3.3.1 and also paragraph 4.4.1 for restrictions on the use of the lateral force analysis method).

4.2 Structural model. The model of the building used in the structural analysis shall fulfil all requirements in clause 4.3.1 of SS EN 1998-1. Refer to clause 4.3.1 (6) & (7)[L] of SS EN 1998-1 for guidance on modelling of cracked behaviour of concrete or composite buildings.

4.3 Storey weight, W_i. The storey weight, W_i at storey i, taken when calculating the seismic actions should comprise the full permanent (or dead) plus the variable (or imposed) load multiplied by a factor Ψ_{Ei}. Clause 4.2.4(2)P of SS EN 1998-1 quantifies Ψ_{Ei} as the factor Ψ_{2i} multiplied by a reduction factor φ that allows for the incomplete coupling between the structure and its imposed load.

$W_{i\,(\text{at storey } i)}$ = dead load + superimposed dead load + (Ψ_{Ei} . imposed load)

where $\Psi_{Ei} = \Psi_{2i}.\varphi$

4.3.1 Recommended values of Ψ_{2i} and φ are reproduced in Table 2, which comprises values taken from Table NA-A1.1 of the National Annex to SS EN 1990 and Clause 4.2.4(2)P of National Annex to SS EN 1998-1.

[L] In concrete and composite buildings, the stiffness of the load bearing elements should, in general, be evaluated taking into account the effect of cracking. Such stiffness should correspond to the initiation of yielding of the reinforcement. Unless a more accurate analysis of the cracked elements is performed, the elastic flexural and shear stiffness properties of concrete and composite elements may be taken to be equal to one-half of the corresponding stiffness of the uncracked elements.

Category of use	Specific use	Ψ_{2i}	φ		
			Roof	Storeys with correlated occupancies	Independently occupied storeys
A	domestic, residential (eg. rooms in residential buildings and houses; bedrooms and wards in hospitals; bedroom in hotels and hotel kitchens and toilets)	0.3	1.0	0.8	0.5
B	offices	0.3	1.0	0.8	0.5
C	congregation of people • areas with tables, etc. (eg. schools, cafes, restaurants, dining halls, reading rooms, receptions); • areas with fixed seats. (eg. churches, theatres or cinemas, conference rooms, lecture halls, assembly halls, waiting rooms, railway waiting rooms; • areas without obstacles for moving people. (eg. museums, exhibition rooms, etc. and access areas in public and administration buildings, hotels, hospitals, railway station forecourts; • areas with possible physical activities. (eg. dance halls, gymnastic rooms, stages); • areas susceptible to large crowds (eg. buildings for public events like concert halls, sports halls including stands, terraces and access areas and railway platforms)	0.6	1.0	0.8	0.5
D	shopping areas (eg. general retail shops and department stores)	0.6	1.0		
E	storage areas and industrial use (eg. archives and areas susceptible to accumulation of goods, including access areas and industrial use)	0.8	1.0		
F	traffic areas (vehicle weight ≤ 30kN)	0.6	1.0		

Table 2 – Recommended values of Ψ_{2i} and φ

4.3.2 Guide on the adoption of value of φ (refer also to illustration below):

In a Category A building, for example a residential building, a φ value of 0.8 is to be adopted for all residential floors (see Figure 6(a)) as these floors are correlated (i.e. interrelated) occupancies. However, if a floor in the residential building is designed as non-residential, for example being designed to house communal facilities, the φ value for that particular floor can be 0.5 (see Figure 6(b)). Likewise, for a hospital or hotel building, a φ value of 0.8 is to be adopted for all the floors housing bedrooms and wards (in the case of hospitals) or bedrooms, kitchens and toilets (in the case of hotels). However, if a floor in the building is designed not for occupancy as bedrooms and wards (in the case of hospitals) or bedrooms, kitchens and toilets (in the case of hotels), for example being designed to house communal facilities (e.g. swimming pool, café, restaurants), the φ value for that particular floor can be 0.5.

In a Category B building (i.e. office building), the same principle will apply, where a φ value of 0.8 is to be adopted for all floors that are designed for office occupancies. However, if a floor in the office building is designed for other occupancy, for example as refuge floor, the φ value for that particular floor can be 0.5.

In a Category C building, which is designed as a building for congregation of people, a φ value of 0.8 is to be adopted for all floors for such occupancy. A φ value of 0.5 can be adopted for a floor which is not related to such occupancy.

In a mixed development comprising, say shopping areas (Category D) on the podium block and residential (Category A) on the tower block, the adoption of φ value would be as follows, and as shown in Figure 6(c):

- a φ value of 0.8 is to be adopted for all floors in the tower block designed for residential occupancy;
- a φ value of 1.0 is to be adopted for all floors in the podium block designed for shopping areas;
- a φ value of 0.5 is to be adopted for a floor in the tower block that is not designed for residential occupancy.

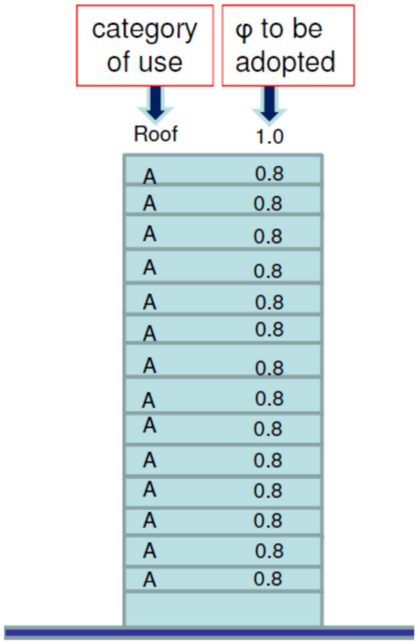


Figure 6(a)

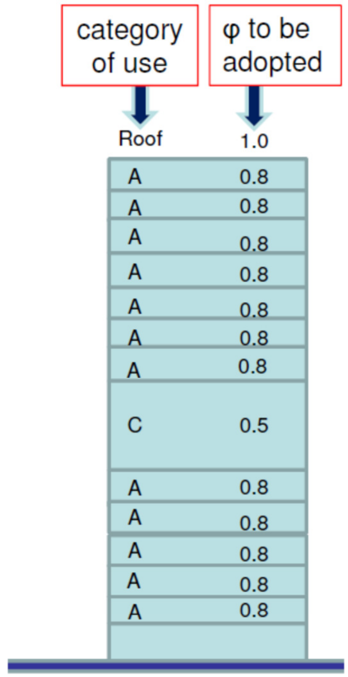


Figure 6(b)

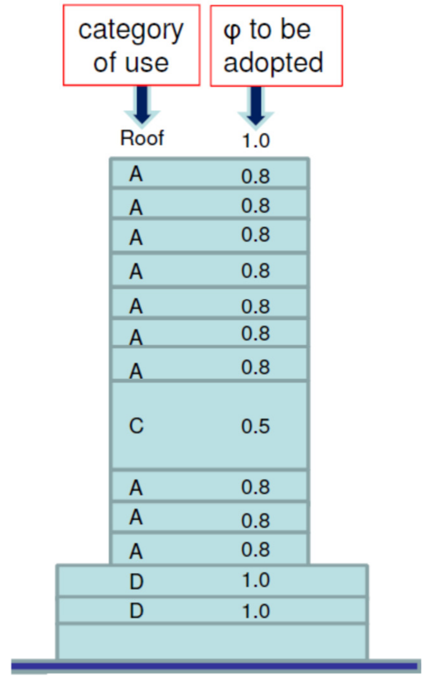
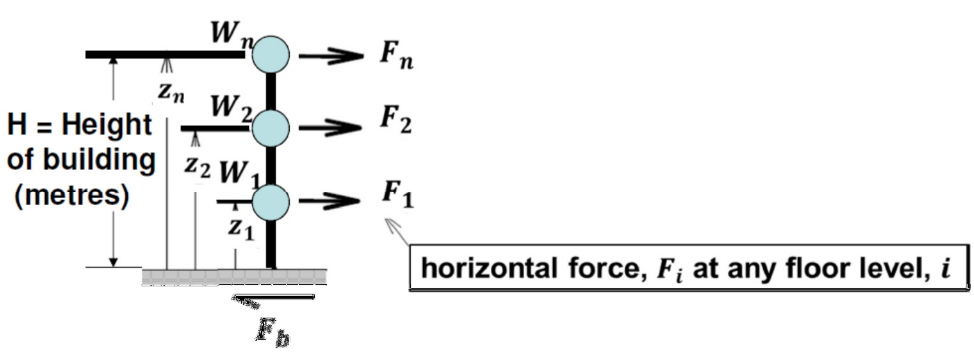


Figure 6(c)

4.4 Lateral Force Analysis Method

4.4.1 The lateral force analysis method is only applicable to buildings with fundamental periods (T_1) of vibration in the two main directions smaller than 2.0s (refer to Clause 4.3.3.2.1(2)a) of SS EN 1998-1) and to buildings that are regular in elevation (refer to Clause 4.2.3.3 of SS EN 1998-1 for definition of regularity in elevation).

4.4.2 Derivation of Seismic Action using Lateral Force Analysis Method. The Seismic Action shall be determined using the lateral load distribution formula given below.



where W_i, W_j are the floor level Storey Weights determined as in paragraph 4.3;

z_i, z_j are the heights of the Storey Weights W_i, W_j above the level of application of the Seismic Action (foundation level or top of a rigid basement);

n is the number of storeys;

W is the total weight of the building

$$\boldsymbol{W} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{W_i}$$

F_b is the base shear due to Seismic Action determined as in paragraph 4.4.3; and

F_i is the horizontal force acting at floor level i.

$$\boldsymbol{F_i = F_b \frac{W_i z_i}{\sum_{j=1}^{n} W_j z_j}}$$

4.4.3 <u>Derivation of base shear due to Seismic Action</u>

- Estimate natural period of building, T_{1x} and T_{1y}, in two main directions based on any of the appropriate equations in Clause 4.3.3.2.2 of SS EN 1998-1;
- Determine $S_d(T_{1x})$, and $S_d(T_{1y})$, which are derived from the equation in paragraph 3.2;
- Determine λ, the correction factor (refer to Clause 4.3.3.2.2 of SS EN 1998-1) which is equal to 0.85 (T_1 has to be less than $2T_C$); and
- Base shear force in the two main directions:

  $F_{b,x} = \frac{S_d(T_{1x})}{g} . W . \lambda$ and

  $F_{b,y} = \frac{S_d(T_{1y})}{g} . W . \lambda$

  where, W is the total weight of the building (refer to paragraph 4.4.2) and g is the gravitational constant = 9.81m/s^2.

4.5 Modal Response Spectrum Analysis Method

4.5.1 Derivation of Seismic Action using Modal Response Spectrum Analysis Method. The design spectrum, $S_d(T)$, derived from paragraph 3.2 shall be used as input directly into any conventional structural analysis software as the lateral Seismic Action when carrying out dynamic analysis using the modal response spectrum method.

4.5.2 Refer to Clause 4.3.3.3.1 2(P) & 3 [M] of SS EN 1998-1 for specific requirements to be satisfied when using the modal response spectrum method.

[M] The response of all modes of vibration contributing significantly to the global response shall be taken into account. This requirement is deemed to be satisfied if either of the following can be demonstrated:

- the sum of the effective modal masses for the modes taken into account amounts to at least 90% of the total mass of the structure;
- all modes with effective modal masses greater than 5% of the total mass are taken into account.

5. Combination of Actions and Accidental Torsional Effects

5.1 The Seismic Action (determined in paragraph 4 using either the lateral force method or the modal response spectrum method) shall be applied at the centre of mass of each floor and the building shall be evaluated for the following Combination of Actions at **Ultimate Limit State (ULS)**:

Combination of Actions at ULS = 1.0 x Storey Weight[N] ± 1.0 x Seismic Action[O] + 1.0 x Geometric Imperfection Effects[P]

5.2 Two Load Cases are to be considered for the Combination of Actions at ULS with 100% of the prescribed Seismic Action applied in one direction and 30% of the Seismic Action applied in the perpendicular direction as shown in Figure 7. Alternatively, the Square Root of the Sum of the Squared Values (SRSS) method, as per Clause 4.3.3.5.1(2)b)[Q] of SS EN 1998-1, may be used.

Figure 7 – Two load cases at Combination of Actions at ULS

[N] Storey Weight, as determined in paragraph 4.3, applied as gravity load.

[O] Seismic Action, determined as in paragraph 4, applied as horizontal forces.

[P] The Geometric Imperfection Effects due to frame imperfections as required in the respective Eurocodes.

[Q] The maximum value of each action effect on the structure due to the two horizontal components of the seismic action may be estimated by the square root of the sum of the squared values of the action effect due to each horizontal component (SRSS method).

5.3 Accidental torsional effects. In order to account for uncertainties in the location of masses and spatial variations of the Seismic Action, the calculated centre of mass at each floor level *i* shall be considered in the combination of actions in paragraph 5 as being displaced from its nominal location in each direction of analysis by an accidental eccentricity, $e_{ai} = \pm 0.05\ L_i$

where e_{ai} *is the accidental eccentricity of storey mass i from its nominal location, taken in the same direction at all floor levels;*

L_i is the floor-dimension perpendicular to the direction of the Seismic Action.

6. Foundation Design

6.1 If Ductility Class Low (DCL) is adopted for the design (refer to paragraph 3.3.2), the reaction forces derived directly from the structural analyses using combinations of actions in paragraph 5 shall be used in the design of foundation elements. Reference shall also be made to BS EN 1998-5 where applicable.

6.2 If Ductility Class Medium (DCM) or Ductility Class High (DCH) is adopted for the design (refer to paragraph 3.3.2), the requirements of Clause 4.4.2.6 of SS EN 1998-1 shall be adhered to.

7. Drift Limitation

7.1 The damage limitation should be verified by limiting the design inter-storey drift, d_r in accordance to the following formula[R] (refer to Clause 4.3.4 and Clause 4.4.3.2(1)a of SS EN 1998-1):

$$\boldsymbol{d_r \leq \frac{0.005h}{v.q}}$$

where d_r is the design interstorey drift, evaluated as the difference of the average lateral displacements, d_e [S] at the top and bottom of the storey under consideration;

v is the reduction factor which takes into account the lower return period of the Seismic Action associated with the damage limitation requirement (refer to Clause 4.4.3.2(2) in National Annex to SS EN 1998-1 on the value of factor "v" to be adopted, namely v = 0.5 for "ordinary buildings" and v = 0.4 for "special buildings");

h is the storey height; and

q is the behaviour factor (refer to paragraph 3.3).

[R] This formula is derived from equation 4.31 from Clause 4.4.3.2(1)a and equation 4.23 from Clause 4.3.4 of SS EN 1998-1.

[S] d_e is the displacement of the same point of the structural system, as determined by the analysis based on the design response spectrum (using the combination of actions in paragraph 5).

8. Minimum Structural Separation for Buildings Above 20m High

8.1 Buildings shall have a minimum structural separation[T] as outlined in paragraphs 8.2 and 8.3 below.

8.2 The minimum structural separation for a new building A from the property boundary line (see Figure 8) <u>at each floor level</u> should be Δ_A, where Δ_A is the deflection of the building at that floor level determined from the structural analysis using the combination of actions in paragraph 5 multiplied by the behaviour factor q adopted based on paragraph 3.3. This minimum structural separation at each floor level should not be less than 0.1% of the height of that floor level measured from the foundation or the top of a rigid basement as defined in paragraph 2.1

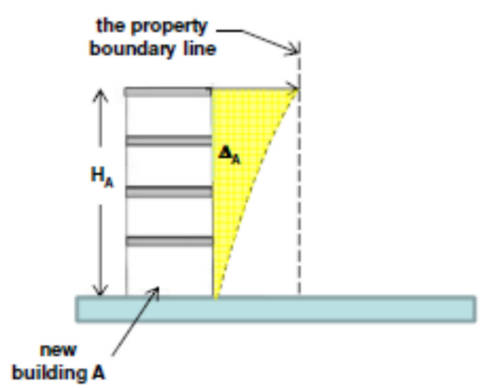


Figure 8 - Minimum structural separation from property boundary line

8.3 The minimum structural separation from adjacent buildings within the same development (see Figure 9), Δ, <u>at each floor level</u> should be the square root of the sum of the squares of the deflections, Δ_A and Δ_B, where Δ_A and Δ_B are the deflections of the two buildings respectively determined from the structural analysis using the combination of actions in paragraph 5 at that floor level multiplied by the behaviour factor q adopted based on paragraph 3.3. This minimum structural separation at each floor level should not be less than 0.14% of the height of that floor level measured from the foundation or the top of a rigid basement as defined in paragraph 2.1.

[T] Minimum structural separation is measured from the key structural elements of the building and does not include architectural finishes.

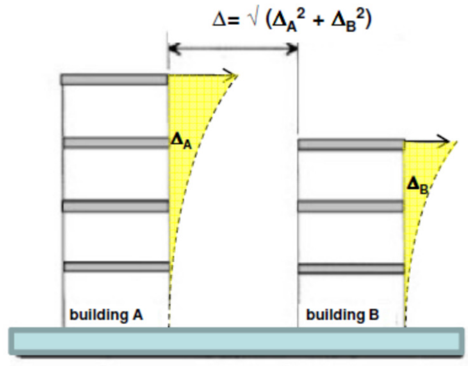


Figure 9 - Minimum structural separation from adjacent buildings within the same development

Building and Construction Authority

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