# A ANNEX A

## A.1 VULNERABILITY INDEX

### A.1.1 General

1 The Vulnerability Index $I_V$ is the sum of the grade of each building characteristic as presented in the relevant tables in the following chapters.

2 Structures such as bridges, underpasses, rigid utility ducts shall be treated as buildings considering their corresponding rigidity.

3 The Stage 2 vulnerability index is the sum of the grade for the characteristics 1 and 5 of each building as presented in the relevant tables in the following chapters. The rest of the procedure for determining the Stage 2 risk coefficient is the same as for Stage 1.

### A.1.2 Vulnerability Index Characteristics and Grades for Buildings within the Influence Zone of the Tunnels

1 Reinforced concrete, structural steel and composite buildings as well as buildings with prestressed concrete elements:

| | Characteristic | Grade |
|---|---|---|
| 1 | **Age of building** | |
| | 60 years < Age | 20 |
| | 40 years < Age ≤ 60 years | 15 |
| | 20 years < Age ≤ 40 years | 10 |
| | Age ≤ 20 years | 5 |
| 2 | **Height H above ground** | |
| | H ≤ 3 m | 3 |
| | 3 m < H ≤ 6 m | 4 |
| | 6 m < H ≤ 9 m | 5 |
| | 9 m < H ≤ 12 m | 6 |
| | 12 m < H ≤ 15 m | 7 |
| | 15 m < H ≤ 18 m | 8 |
| | 18 m < H ≤ 21 m | 9 |
| | 21 m < H ≤ 24 m | 10 |
| | 24 m < H ≤ 27 m | 11 |
| | 27 m < H ≤ 30 m | 12 |
| | 30 m < H | 13 |
| 3 | **Number of underground storeys / basements** | |
| | 0 | 5 |
| | 1 | 10 |
| | ≥ 2 | 15 |
| 4 | **Foundation type** | |
| | Pile foundation at a distance of less than one diameter from the tunnel lining | 30 |
| | Pile foundation at a distance of more than one diameter from the tunnel lining | 25 |
| | Spread footings without tie beams | 20 |
| | Spread footings with tie beams | 15 |
| | Strip foundation | 10 |
| | Raft foundation | 5 |
| 5 | **History of damages** | |
| | Damages beyond repair to the structural system | 20 |
| | Repairable damages to the structural system | 15 |
| | Damages to filling elements | 10 |
| | No damages | 0 |

| | Characteristic | Grade |
|---|---|---|
| 6 | **Extensions to length (*)** | |
| | Yes | 15 |
| | No | 0 |
| 7 | **Additions to height** | |
| | Yes | 15 |
| | No | 0 |
| 8 | **Interventions to the structural system** | |
| | Yes | 15 |
| | No | 0 |
| 9 | **Contact with other buildings** | |
| | Contact on three or more sides | 15 |
| | Contact on two sides | 10 |
| | Contact on one side | 5 |
| | No contact | 0 |
| 10 | **Subsoil problems** | |
| | At a distance of up to 5 m from the building | 20 |
| | At a distance of 5 m to 15 m from the building | 10 |
| | No problems | 0 |
| 11 | **Presence of a ground floor storey with big height (**)** | |
| | Yes | 10 |
| | No | 0 |
| 12 | **Layout of vertical structural elements** | |
| | Irregular | 15 |
| | Intermediate | 10 |
| | Regular | 5 |
| 13 | **Density of vertical structural elements (length L of dominant clear spans)** | |
| | L ≥ 10 m | 20 |
| | 7 m ≤ L < 10 m | 15 |
| | 5 m ≤ L < 7 m | 10 |
| | L < 5 m | 5 |

(*) If the extension to length is structurally independent from the initial building, then the initial building and the extension shall be examined as separate buildings. Otherwise, the initial building and the extension shall be examined as a unified structure and for the determination of the Vulnerability Index the most adverse value of each criterion shall be taken into account. In this case, if the initial building or the extension has bearing masonry as structural system the unified structure shall be considered as having bearing masonry as structural system.

(**) Big height is defined as at least 1.5 times the height of a typical storey.

In case one characteristic is not known or in case of doubt, the most adverse grade shall be considered. Adverse is the grade that leads to increase of the Vulnerability index.

2 Buildings with load bearing masonry:

| | Characteristic | Grade |
|---|---|---|
| 1 | **Age of building** | |
| | 80 years < Age | 15 |
| | 30 years < Age ≤ 80 years | 10 |
| | Age ≤ 30 years | 5 |
| 2 | **Height H above ground** | |
| | H ≤ 3 m | 5 |
| | 3 m < H ≤ 6 m | 10 |
| | 6 m < H | 15 |
| 3 | **Number of basements** | |
| | No basement | 5 |
| | One basement extending to part of the ground floor plan view | 10 |
| | One or more full basements | 15 |
| 4 | **Foundation type** | |
| | Foundation on boulder cones | 20 |
| | Spread footings without tie beams | 15 |
| | Spread footings with tie beams | 10 |
| | Strip foundation of concrete | 5 |
| 5 | **History of damages** | |
| | Damages beyond repair to the structural system | 25 |
| | Repairable damages to the structural system | 15 |
| | Damages to filling elements | 10 |
| | No damages | 0 |
| 6 | **Extensions to length (*)** | |
| | Yes | 15 |
| | No | 0 |
| 7 | **Additions to height** | |
| | Yes | 15 |
| | No | 0 |
| 8 | **Interventions to the structural system** | |
| | Yes | 15 |
| | No | 0 |

| | Characteristic | Grade |
|---|---|---|
| 9 | **Contact with other buildings** | |
| | Contact on three or more sides | 15 |
| | Contact on two sides | 10 |
| | Contact on one side | 5 |
| | No contact | 0 |
| 10 | **Subsoil problems** | |
| | At a distance of up to 5 m from the building | 20 |
| | At a distance of 5 m to 15 m from the building | 15 |
| | No problems | 0 |
| 11 | **Overall condition of the masonry** | |
| | Inadequate | 15 |
| | Adequate | 10 |
| | Very good | 0 |
| 12 | **Layout of vertical bearing elements** | |
| | Irregular | 15 |
| | Intermediate | 10 |
| | Regular | 5 |
| 13 | **Density of vertical structural elements (length L of dominant clear spans)** | |
| | L ≥ 3 m | 10 |
| | L < 3 m | 5 |

(*) If the extension to length is structurally independent from the initial building, then the initial building and the extension shall be examined as separate buildings. Otherwise, the initial building and the extension shall be examined as a unified structure and for the determination of the Vulnerability Index the most adverse value of each criterion shall be taken into account. In this case, if the initial building or the extension has bearing masonry as structural system the unified structure shall be considered as having bearing masonry as structural system.

In case one characteristic is not known or in case of doubt, the most adverse grade shall be considered. Adverse is the grade that leads to increase of the Vulnerability index.

**A.1.3 Vulnerability Index Characteristics and Grades for Buildings within the Influence Zone of the Rest of the Underground Structures**

1 Reinforced concrete, structural steel and composite buildings as well as buildings with prestressed concrete elements:

| | Characteristic | Grade |
|---|---|---|
| 1 | **Age of building** | |
| | 60 years < Age | 20 |
| | 40 years < Age ≤ 60 years | 15 |
| | 20 years < Age ≤ 40 years | 10 |
| | Age ≤ 20 years | 5 |
| 2 | **Height H above ground** | |
| | H ≤ 3 m | 3 |
| | 3 m < H ≤ 6 m | 4 |
| | 6 m < H ≤ 9 m | 5 |
| | 9 m < H ≤ 12 m | 6 |
| | 12 m < H ≤ 15 m | 7 |
| | 15 m < H ≤ 18 m | 8 |
| | 18 m < H ≤ 21 m | 9 |
| | 21 m < H ≤ 24 m | 10 |
| | 24 m < H ≤ 27 m | 11 |
| | 27 m < H ≤ 30 m | 12 |
| | 30 m < H | 13 |
| 3 | **Number of underground storeys / basements** | |
| | 0 | 15 |
| | 1 | 10 |
| | ≥ 2 | 5 |
| 4 | **Foundation type** | |
| | Spread footings without tie beams | 20 |
| | Spread footings with tie beams | 15 |
| | Strip foundation | 10 |
| | Raft foundation and / or piles | 5 |
| 5 | **History of damages** | |
| | Damages beyond repair to the structural system | 20 |
| | Repairable damages to the structural system | 15 |
| | Damages to filling elements | 10 |
| | No damages | 0 |

| | Characteristic | Grade |
|---|---|---|
| 6 | **Extensions to length (*)** | |
| | Yes | 15 |
| | No | 0 |
| 7 | **Additions to height** | |
| | Yes | 15 |
| | No | 0 |
| 8 | **Interventions to the structural system** | |
| | Yes | 15 |
| | No | 0 |
| 9 | **Contact with other buildings** | |
| | Contact on three or more sides | 15 |
| | Contact on two sides | 10 |
| | Contact on one side | 5 |
| | No contact | 0 |
| 10 | **Subsoil problems** | |
| | At a distance of up to 5 m from the building | 20 |
| | At a distance of 5 m to 15 m from the building | 10 |
| | No problems | 0 |
| 11 | **Presence of a ground floor storey with big height (**)** | |
| | Yes | 10 |
| | No | 0 |
| 12 | **Layout of vertical structural elements** | |
| | Irregular | 15 |
| | Intermediate | 10 |
| | Regular | 5 |
| 13 | **Density of vertical structural elements (length L of dominant clear spans)** | |
| | L ≥ 10 m | 20 |
| | 7 m ≤ L < 10 m | 15 |
| | 5 m ≤ L < 7 m | 10 |
| | L < 5 m | 5 |

(*) If the extension to length is structurally independent from the initial building, then the initial building and the extension shall be examined as separate buildings. Otherwise, the initial building and the extension shall be examined as a unified structure and for the determination of the Vulnerability Index the most adverse value of each criterion shall be taken into account. In this case, if the initial building or the extension has bearing masonry as structural system the unified structure shall be considered as having bearing masonry as structural system.

(**) Big height is defined as at least 1.5 times the height of a typical storey.

In case one characteristic is not known or in case of doubt, the most adverse grade shall be considered. Adverse is the grade that leads to increase of the Vulnerability index.

2 Buildings with load bearing masonry:

| | Characteristic | Grade |
|---|---|---|
| 1 | **Age of building** | |
| | 80 years < Age | 15 |
| | 30 years < Age ≤ 80 years | 10 |
| | Age ≤ 30 years | 5 |
| 2 | **Height H above ground** | |
| | H ≤ 3 m | 5 |
| | 3 m < H ≤ 6 m | 10 |
| | 6 m < H | 15 |
| 3 | **Number of basements** | |
| | No basement | 15 |
| | One basement extending to part of the ground floor plan view | 10 |
| | One or more full basements | 5 |
| 4 | **Foundation type** | |
| | Foundation on boulder cones | 20 |
| | Spread footings without tie beams | 15 |
| | Spread footings with tie beams | 10 |
| | Strip foundation of concrete | 5 |
| 5 | **History of damages** | |
| | Damages beyond repair to the structural system | 25 |
| | Repairable damages to the structural system | 15 |
| | Damages to filling elements | 10 |
| | No damages | 0 |
| 6 | **Extensions to length (*)** | |
| | Yes | 15 |
| | No | 0 |
| 7 | **Additions to height** | |
| | Yes | 15 |
| | No | 0 |
| 8 | **Interventions to the structural system** | |
| | Yes | 15 |
| | No | 0 |

| | Characteristic | Grade |
|---|---|---|
| 9 | **Contact with other buildings** | |
| | Contact on three or more sides | 15 |
| | Contact on two sides | 10 |
| | Contact on one side | 5 |
| | No contact | 0 |
| 10 | **Subsoil problems** | |
| | At a distance of up to 5 m from the building | 20 |
| | At a distance of 5 m to 15 m from the building | 15 |
| | No problems | 0 |
| 11 | **Overall condition of the masonry** | |
| | Inadequate | 15 |
| | Adequate | 10 |
| | Very good | 0 |
| 12 | **Layout of vertical bearing elements** | |
| | Irregular | 15 |
| | Intermediate | 10 |
| | Regular | 5 |
| 13 | **Density of vertical structural elements (length L of dominant clear spans)** | |
| | L ≥ 3 m | 10 |
| | L < 3 m | 5 |

(*) If the extension to length is structurally independent from the initial building, then the initial building and the extension shall be examined as separate buildings. Otherwise, the initial building and the extension shall be examined as a unified structure and for the determination of the Vulnerability Index the most adverse value of each criterion shall be taken into account. In this case, if the initial building or the extension has bearing masonry as structural system the unified structure shall be considered as having bearing masonry as structural system.

In case one characteristic is not known or in case of doubt, the most adverse grade shall be considered. Adverse is the grade that leads to increase of the Vulnerability index.

## A.2 STAGE 2 RISK ASSESSMENT

### A.2.1 Type I Structures – General

1 This assessment stage is based on the calculated equivalent tensile strain due to the combined effects of bending, shear deformation and horizontal tensile strain. A separate analysis shall be performed for each side of the building.

2 Each side of the building of Figure A.1 (a) shall be simulated by an equivalent isotropic or anisotropic elastic beam (see also clause A.2.5) with length L and height H shown in Figure A.1 (b). The foundation of the beam shall be considered to follow the ground movements.

3 The ground deformation in Figure A.1 (c) causes settlements to the building in the form of sagging and / or hogging. The building is subject to two types of strain: the bending strain and the shearing strain (Figure A.2)

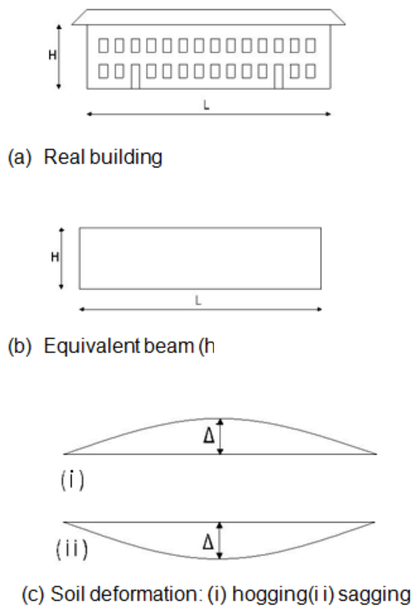



**Figure A.1 Real Building – Equivalent Beam – Hogging and Sagging**

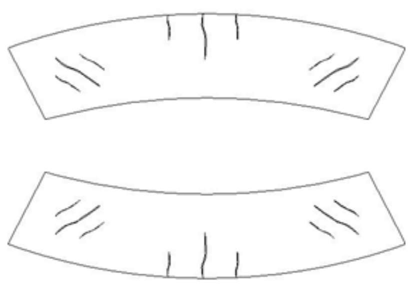


**Figure A.2 Strains and Cracking**

### A.2.2 Sagging and Hogging

1 Figure A.3 gives an example of a long building at the culminating point of the settlement trough caused by a neighbouring excavation. The building is subject to sagging and hogging. Each side of the building is thus divided into two distinct parts which are analysed and checked separately.

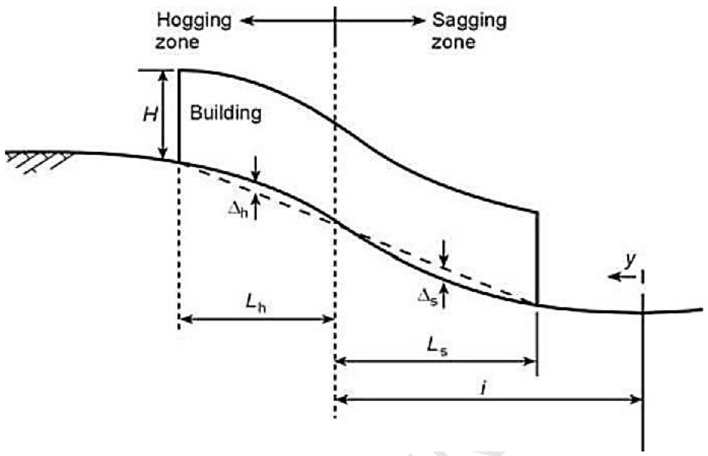



**Figure A.3 Hogging and Sagging - Deformations**

Symbols and their explanation in the above picture:

H = height of the building side

L = length of the building side

$L_s$ = sagging length

$L_h$ = hogging length

I = distance of the zones limit from edge of excavation or from the centre of the tunnel

$\Delta_s$ = differential settlement of the base of the side (assumed as straight line) in the sagging zone(*)

$\Delta_h$ = differential settlement of the base of the side (assumed as straight line) in the hogging zone(*)

(*) the settlements shall be calculated by finite elements analysis which shall assume green-field conditions, i.e. only the weight of the building is taken into account and not its stiffness.

2 The two above forms of deformation have different effects on the equivalent beam and as a result on its behaviour in bending and shear.

In the case of hogging the neutral axis of the equivalent beam is located at the lower side of the beam. The moment of inertia of the equivalent beam is in this case $I_h = H^3/3$.

In the case of sagging the neutral axis of the equivalent beam is located in the middle of the beam height. The moment of inertia of the equivalent beam is in this case $I_h = H^3/12$.

### A.2.3 Equivalent Beam Behaviour in Bending – Maximum Equivalent Tensile Strain

1 The following equations shall be used to calculate the maximum equivalent tensile strain due to bending:

(a) For sagging: $\frac{\Delta_s}{L_s} = \frac{1}{5} \times \left( \frac{L_s}{1.2 \times H} + \frac{H}{L_s} \times \frac{E}{G} \right) \times \varepsilon_{b,\max}$

(b) For hogging: $\frac{\Delta_h}{L_h} = \frac{1}{10} \times \left( \frac{L_h}{1.2 \times H} + \frac{4H}{L_h} \times \frac{E}{G} \right) \times \varepsilon_{b,\max}$

2 In the above equations $E$ and $G$ are the equivalent beam Young's modulus and shear modulus respectively (see clause A.2.5 for the elastic constants of the equivalent beams).

### A.2.4 Equivalent Beam Behaviour in Shear – Maximum Equivalent Tensile Strain

1 At the ends of the equivalent beam (in areas at a distance of $L/4$ from its edges) occur the diagonal maximum tensile stresses due to shear. The following equations shall be used for their calculation:

(a) For sagging: $\frac{\Delta_s}{L_s} = \left( 1 + \frac{2 \times L_s^2}{3 \times H^2} \times \frac{G}{E} \right) \times \varepsilon_{d,\max}$

(b) For hogging: $\frac{\Delta_h}{L_h} = \left( 1 + \frac{L_h^2}{6 \times H^2} \times \frac{G}{E} \right) \times \varepsilon_{d,\max}$

2 In the above equations $E$ and $G$ are the equivalent beam Young's modulus and shear modulus respectively (see clause A.2.5 for the elastic constants of the equivalent beams).

### A.2.5 Elastic Constants of the Equivalent Beam

1 The following values shall be considered when modelling each side of the building as an equivalent beam:

(a) For buildings sides modelled as a homogenous and isotropic beam: $\frac{E}{G} = 2.5$

(b) There are cases where the building side needs to be considered as an anisotropic beam. See cases and respective values below:

(i) Unfilled concrete frames with considerable horizontal stiffness due to slabs and/or beams: $\frac{E}{G} = 12.5$

(ii) Masonry filled frames or masonry having openings at their outer edges under shear: $\frac{E}{G} = 10.0$

(iii) Masonry with low horizontal stiffness subject to tensile strain of the ground: $\frac{E}{G} = 1.0$ for sagging, $\frac{E}{G} = 0.5$ for hogging

### A.2.6 Horizontal Tensile Strains

1 When the ground deforms due to an excavation or due to tunnelling construction it does not deform only vertically but also horizontally. The equivalent beam is subject to horizontal tensile strain $\varepsilon_h$ due to the different values of horizontal deformation along its length. The horizontal tensile strain shall be calculated by means of finite elements analysis.

### A.2.7 Influence of the Horizontal Tensile Strains

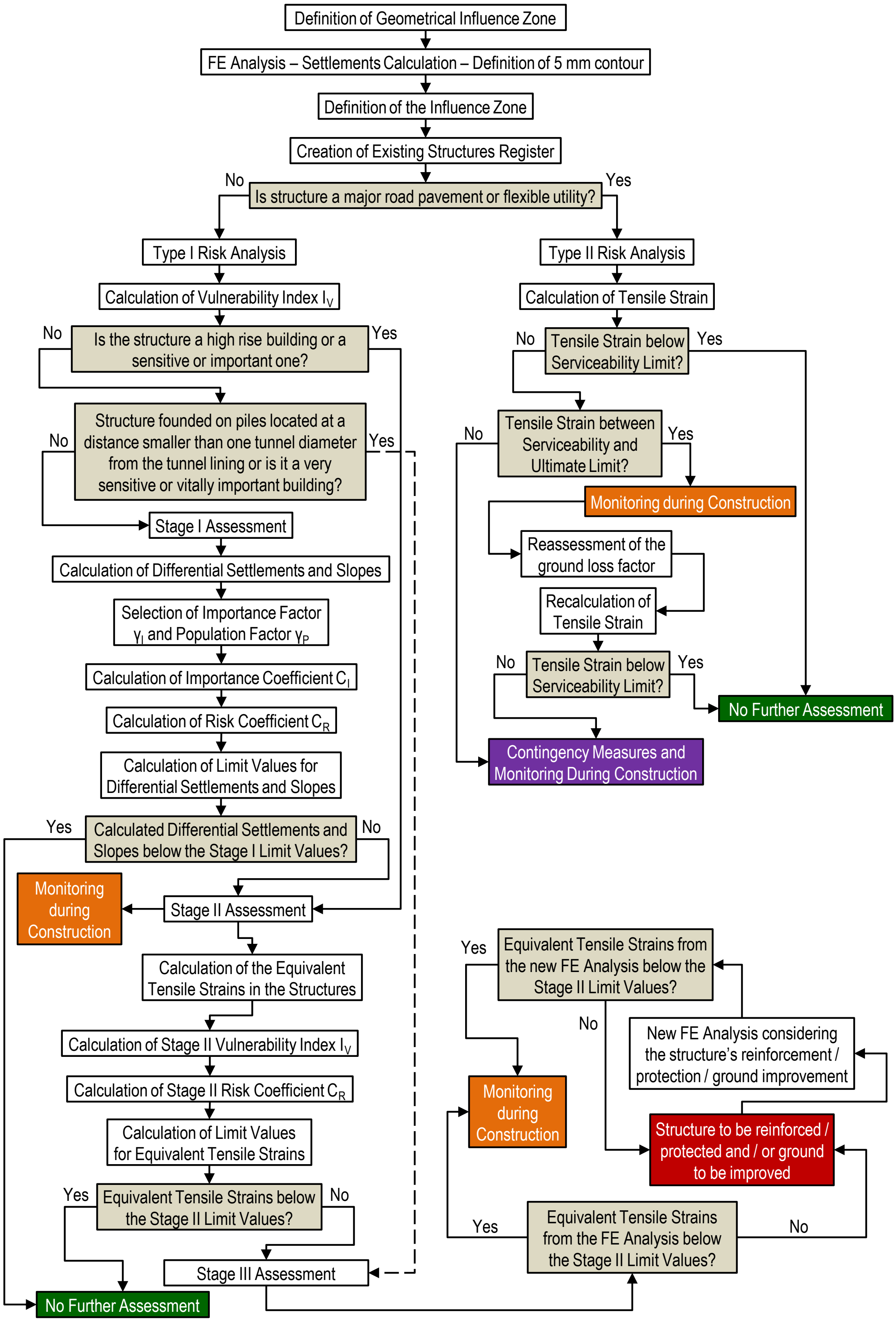
1 The horizontal tensile strains described above shall be superimposed with the maximum tensile stresses due to bending and shear (as described in A.2.3 and A.2.4) for sagging and hogging as follows:

(a) For bending: $\varepsilon_{t,b,\max} = \varepsilon_h + \varepsilon_{b,\max}$

(b) For shear: $\varepsilon_{t,d,\max} = \varepsilon_h \times \left(\frac{1-\nu}{2}\right) + \sqrt{\varepsilon_h^2 \times \left(\frac{1-\nu}{2}\right)^2 + \varepsilon_{d,\max}^2}$. In this equation $\nu$ is the Poisson ratio and shall have the value of 0.25 for the case of isotropic beams whereas for anisotropic beams it shall be calculated on the basis of the $\frac{E}{G}$ values.

2 The maximum total tensile strain $\varepsilon_{\max}$ in the equivalent beam is the maximum of $\varepsilon_{t,b,\max}$ and $\varepsilon_{t,d,\max}$ : $\varepsilon_{\max} = \max\{\varepsilon_{t,b,\max};\varepsilon_{t,d,\max}\}$. This value shall then be used in conjunction with Table 13.6.2 to assess the potential associated Category of Damage.

## A.3 STRUCTURES RISK ASSESSMENT FLOWCHART

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