EC8 Webinars

EAEE European Commission

Second Generation of Eurocode 8

EN 1998-5:2020 - Section 11: Underground Structures

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11 UNDERGROUND STRUCTURES

- **New section** in EN 1998-5
- The section is limited to the **determination of action effects on underground structures**
- **It does not cover design verifications!**

11 UNDERGROUND STRUCTURES

- **Structure / Contents:**

11 UNDERGROUND STRUCTURES

- **Associated Annexes**

Annex G (Informative) Simplified evaluation of peak ground motion parameters for seismic design of underground structures

Annex H (Informative) Simplified analytical expressions for the seismic design of tunnels

Annex I (Informative) Impedance functions for underground structures

11.1 GENERAL

11.1 GENERAL

- **(1) P Tunnels** (bored, cut and cover, immersed) and **underground structures** (culverts and underground large works, like metro and parking stations, pipelines) shall be designed to provide seismic performance consistent with the limit states defined in EN 1998-1–1:2019, 4.4.1(1), EN 1998-3:2019, 4.1(2), and the associated seismic actions

- **(2) P** Underground structures shall be **designed against**:

  ground shaking

  permanent ground deformations due to seismic fault crossing, seismically induced landslides and liquefaction induced phenomena

11.1 GENERAL

- **(3)** Tunnels and other underground structures should **primarily be designed** to accommodate the **transient and permanent deformations**

  Why? The imposed ground deformations (transient and permanent) on underground structures are more important than transient seismic loads related to the structure's inertia

- **(4)** **Spatially extended underground structures:** seismic design in the transverse and longitudinal direction should consider the **spatial variability of the ground motion** and the associated phenomena

11.1 GENERAL

- **(5) Soil-structure-interaction effects** should be considered according to the general rules in § 8, complemented with the provisions of § 11.3

- **(6) Seismic earth pressures** may be estimated according to § 10.3, and duly adjusted with the provisions of § 11.3

11.2 SEISMIC ACTIONS

11.2.1 GENERAL REQUIREMENTS

- **(1)** Estimation of **seismic actions due to ground shaking**

  Acc. to EN1998-1-1:2019 after adjustment accounting for the **depth** and **dimensions** of the underground structure and the **spatial variability** of ground motion

  Annex A provides guidance on the estimation of ground motion

11.2.1 GENERAL REQUIREMENTS

- **(2)** Underground structures crossing potentially **active faults**

  Potentially active faults defined as in § 7.1.2

  Necessary parameters that should be estimated are the **angle of incidence, dip and offset at the location of the structure**

- **(3)** **Effects by precarious slopes** on tunnels/culverts

  Specific ground response and slope stability analyses should be carried out to estimate the type and magnitude of **permanent slope displacements** in the seismic design situation, according to § 7.2

11.2.1 GENERAL REQUIREMENTS

- **(4)** Underground structures in **potentially liquefiable soils**

  Specific ground response and liquefaction assessment should be carried out, according to § 7.5 and § 7.3, aimed at estimating the spatial variability of liquefaction and the severity of **buoyancy effects**

- **(5) Sites susceptible to hazards such as active faults, precarious slopes and potentially liquefiable soils should be avoided**, unless specific design and construction actions reduce the risk to acceptable limits!

11.2.2 GROUND MOTION PARAMETERS

- **(1)** Ground motion parameters should be established for the seismic design of tunnels and underground structures

- **(2)** **Low and moderate seismic action classes** → peak ground motion parameters ***PGA, PGV, PGD*** may be used

  Design response spectra should be consistent with these parameters

- **(3)** For the evaluation of parameters at ground surface, various depths of the embedded structure, and at the depth of the base of the underground structure: **A ground-specific response analysis may** be carried out for this purpose

11.2.2 GROUND MOTION PARAMETERS

- **(4) Moderate and high seismic action classes → a ground-specific response analysis should** be carried out along the total length of the structure

- **(5)** For **low seismic action classes** and in the absence of site-specific ground response analysis, the **ground motion parameters at depth z** in clauses (1) and (2) may be calculated from ***PGA*** at ground surface, (e.g., EN 1998–1–1:2019, 5.2.2.4) using simplified expressions

- **(6)** In the absence of site-specific response analysis the values of ***PGV*(z)** and ***PGD*(z)** may be estimated using empirical correlations

Annex G provides simplified expressions and empirical relations

11.2.2 GROUND MOTION PARAMETERS

- **Annex G** provides:
  - Simplified relations to estimate ***PGA*** distribution with depth
  - Empirical correlations between ***PGA, PGV*** and ***PGD***
  - Formulae to estimate **ground shear stresses** distribution with depth
  - Recommendations for the estimation **of spatial variation and incoherence of the ground motion**

11.2.2 GROUND MOTION PARAMETERS

- **(7)** For the **seismic action in the longitudinal direction of tunnels** **and pipelines**, an **apparent velocity (V_{app})** should be considered.

- **(8)** Absence of site–specific studies? V_{app} may be taken equal to 1000 m/s

11.2.2 PERMANENT GROUND DISPLACEMENT PARAMETERS

- **(1)** For **seismic faulting, seismically triggered landslides, or liquefaction**, as defined in § 7.1.1, § 7.2 and § 7.3, the **permanent ground displacements** should be calculated together with other relevant design parameters **for the design return period and the category of structures under consideration**

- **(2)** For permanent ground displacements not covered in (1), specific studies should be performed

11.3 METHODS OF ANALYSIS

11.3.1 SEISMIC ACTION FOR UNDERGROUND STRUCTURES

- **(1)** For the seismic design of underground structures, the **transient effect of the seismic action** may be expressed in terms of:

  a) **Forces in the transverse direction** (as per § 11.3.2.1)

  b) **Ground deformations in both transverse and longitudinal directions** (as per §11.3.2.2)

- **(2)** The effect of seismic action due to **permanent ground deformation** should be expressed in terms of **displacements** (as per § 11.3.3)

11.3.2 TRANSIENT SEISMIC ACTION

11.3.2.1 FORCES IN THE TRANSVERSE DIRECTION

- **(1)** Estimation of **seismic earth pressures** acting on the structures in the transverse direction? → **methods as per clauses of § 10.3** may be used

- **IMPORTANT NOTE!**
  - Methods as in § 10.3 are appropriate for **shallow tunnels**, culverts and other underground mainly **cut-and cover** structures
  - For **deep** tunnels and undergrounds structures, like metro and parking stations, this approach involves **uncertainties** and the method in § 11.3.2.2 is preferred

11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **(1) Analysis methods** should be based on the main **dynamic response patterns** due to the seismic ground excitation and wave propagation

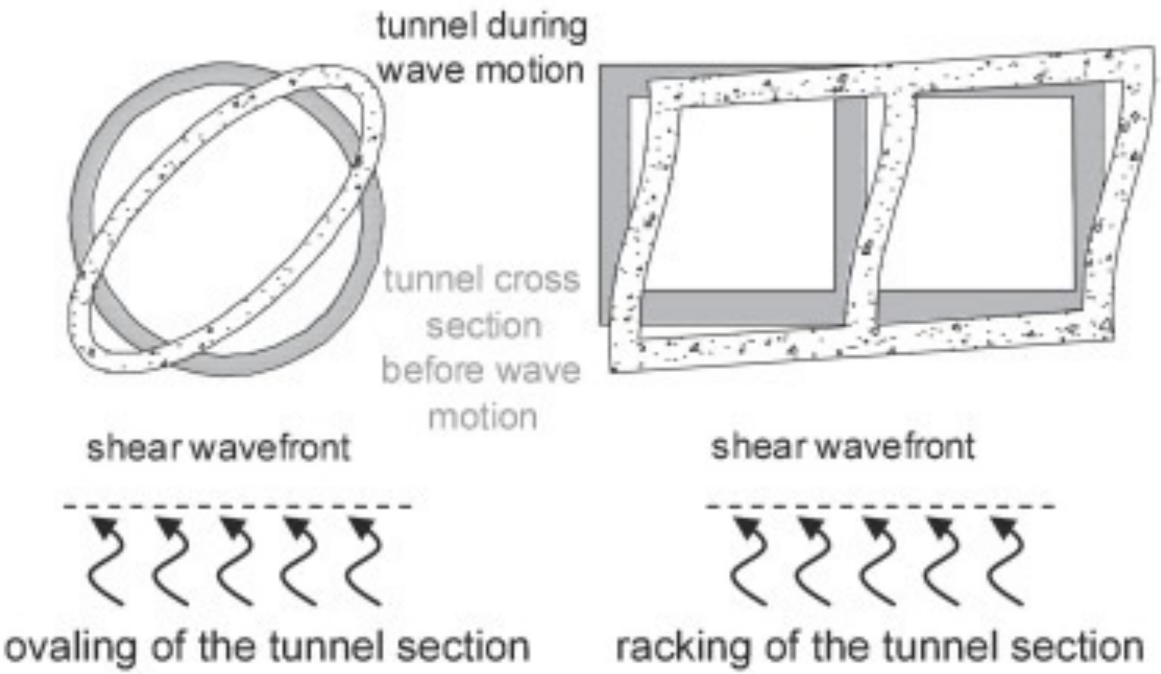
  Two **main deformation modes** should be considered for **transverse response** of tunnels, in a) or b) as appropriate:

  a) **Ovaling response in circular or horse-shoe type tunnels**

  b) **Racking-rocking response in rectangular cut-and-cover tunnels**

11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **Main deformation modes** for transverse response of tunnels



11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **(2)** How to determine the response due to seismic deformation in transverse direction ? Use of:

  Closed form analytical solutions, with or without consideration of soil-structure interaction effects

  Advanced numerical methods (preferable for high seismic action classes)

  Annex H provides expressions for the closed form solutions

11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **(3), (4) Analysis when soil-structure interaction is ignored** → it may be assumed that free-field ground shear deformations along the depth of the tunnel are directly applied statically to the lining to compute the seismic loadings

  Annex H provides guidance for the calculations of the internal forces

11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- (5), (6) **Analysis when soil-structure-interaction effects are considered →**

  In cases of **circular tunnels**, simplified analytical expressions accounting for the **relative flexibility of the structure and the soil** may be used

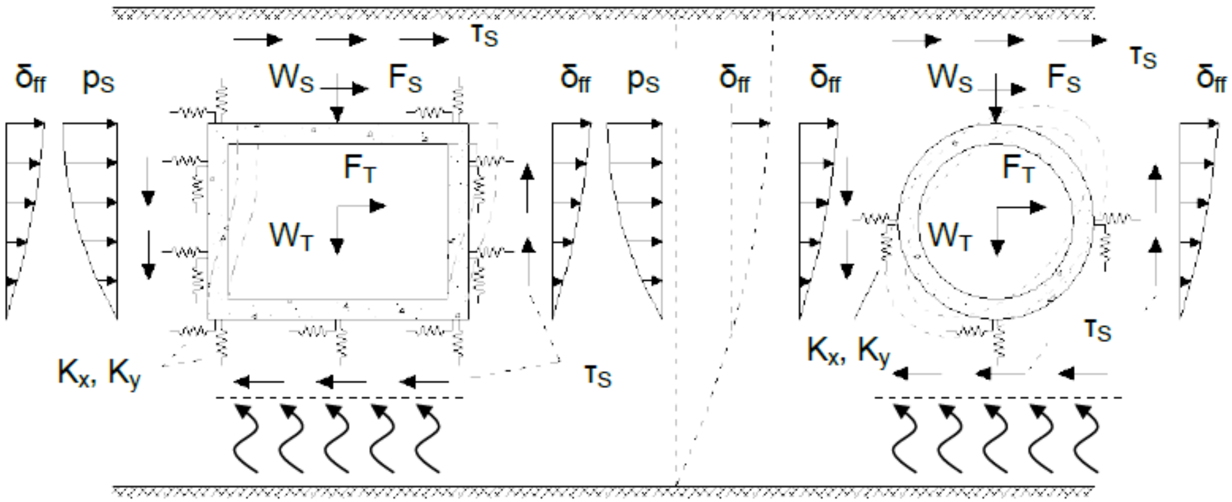
  Annex H provides such simplified analytical expressions

  In cases of **cut-and–cover rectangular tunnels**, the seismic analysis may be based on methods accounting for the **flexibility ratio of the tunnel to the surrounding ground**

  Annex H provides guidance on these methods

11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **(7)** When **soil-structure interaction effects are considered** for the seismic analysis in the **transverse direction**, the model may follow § 8.3 using springs (normal and tangential) consistent with the vibration modes and the dominating deformation pattern



11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **(8) Springs stiffnesses** in (7) should depend on the soil type where the underground structure is embedded, the type of the underground structure, the deformation modes, the seismic strain amplitude for the design ground shaking and the soil strength limit states

  Annex I provides guidance for the calculations of the springs stiffnesses

11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **(9)** For the seismic analysis in the **longitudinal direction** of tunnels and other long underground structures, **when soil-structure interaction effects are neglected**, the analysis may assume that the **longitudinal strains in the tunnel are equal to the ground motion strains in the free-field due to the passage of seismic waves**

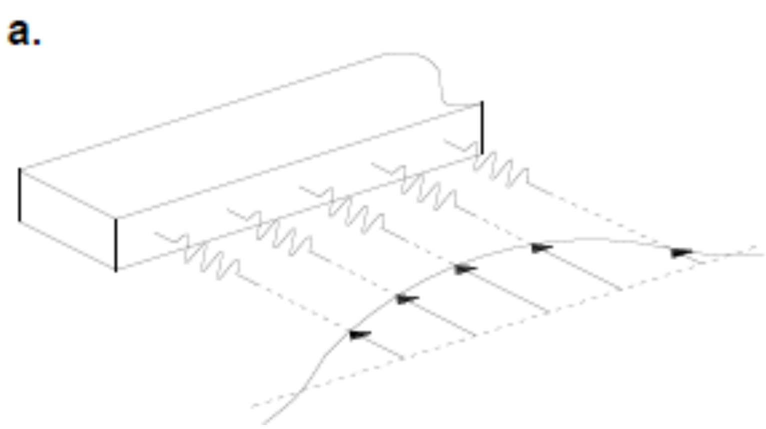
  Annex H provides guidance for the calculations of the strains

11.2.2 GROUND MOTION PARAMETERS

- To sum up, **Annex H** provides:
  - **Simplified relations** for the computation of deformations and lining forces of **circular tunnels** subjected to **ground shaking in the transverse direction**, when considering or neglecting SSI phenomena
  - **Simplified methods** for the computation of deformations and lining forces of **rectangular underground structures** subjected to **ground shaking in the transverse direction,** when considering SSI phenomena
  - **Simplified relations** for the computation of deformations and lining forces of **tunnels and underground structures** subjected to **ground shaking in the longitudinal direction**, when considering or neglecting SSI phenomena

11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **(10)** For the seismic analysis in the **longitudinal direction** of long underground structures, **when soil-structure interaction effects are accounted for**, the analysis may be based on the **Beam-on-Dynamic-Winkler foundation approach** with selection of the values of springs and dashpots to simulate the shear (tangential) and normal soil-structure interaction



11.3.2.2 GROUND DEFORMATION IN TRANSVERSE & LONGITUDINAL DIRECTION

- **Annex I** provides guidance for the calculations of the springs and dashpots

- Soil-structure-interaction effects in the longitudinal direction generally reduce the internal forces in the lining

- The reduction for ordinary ratios of soil to structure stiffness is relatively small

11.3.3 PERMANENT GROUND DEFORMATION

- The **greatest risk** to underground structures is the potential for **large ground movements** as a result of fault crossing, landslides and liquefaction hazards

- In general, it is **not easy to design underground structures to withstand large permanent ground displacements!**

- A preferred strategy is to **avoid any potential site susceptible to these hazards!**

11.3.3 PERMANENT GROUND DEFORMATION

- **(1)** Estimation of **permanent ground displacements for landslide and liquefaction hazards?**

  Acc. to § 7.2.2.3 and § 7.3.5(6) or other properly validated approaches

  Empirical relationships that correlate displacements to earthquake magnitude and fault type may introduce very high uncertainties

11.3.3 PERMANENT GROUND DEFORMATION

- **(2), (3)** When it is **impossible to avoid crossing landslide and liquefaction prone areas**, **ground stabilisation** or **appropriate design** of structures **to undertake** potential **deformations** should be made
- **(4)** In case it cannot be **verified that liquefaction will not occur** in the seismic design situation, the **design should account for buoyancy effects**
- **(5)** Analysis of tunnels against **dip slip faulting (normal and reverse)**, perpendicular to the tunnel axis may be based on a procedure analysis applied to pipelines

  To comply with (5), different approaches may be also applied (i.e. oversize excavation, use of compressible backfill material, design and manufacture of the joints to absorb gradually the longitudinal fault displacements)

11.3.3 PERMANENT GROUND DEFORMATION

- **(6)** For **strike slip faulting**, countermeasures similar to (5) should be taken to minimize the consequences of the faulting offset

- **(7), (8)** Estimation of spatial distribution and attenuation of the maximum fault displacements along the tunnel axis?

  via empirical relations or

  numerically using appropriate 2D or 3D numerical approaches simulating the ground and the fault offset geometry and mechanism (preferable for **high seismic action classes**, where the soil-segmented tunnel interaction should be adequately modelled)

11.3.3 PERMANENT GROUND DEFORMATION

- **(9)** To comply with (5), the **joints of segmented lining** should be **able to accommodate** the permanent ground displacements along the tunnel axis and on both sides of the faulting zone
- **Joints having special design features and capacities** should be used in case of large fault displacements
- **NOTE** For fault displacements exceeding **800 mm-1000 mm**, it can be difficult to structurally accommodate the imposed ground displacements using specially designed joints, and other solutions need to be investigated and implemented!
- **(10) Similar approaches to (7)** should also be applied in case of excessive permanent displacements caused by **landslides and liquefaction**

11.4 SEISMIC LOADING FOR LARGE UNDERGROUND SPACES

11.4.1 GROUND SHAKING

- **(1) Analysis of large underground structures** (e.g. parking garage, metro stations)?

  Analysis accounting explicitly for structure and ground response, including soil-structure interaction effects

- **(2) Pseudo static analysis, as per § 10.3.2**, where the underground structure is modelled as frame structure subjected to static and dynamic earth pressures, **should not be used unless both a) and b) apply**:

  a) the distribution of total earth pressures (static and dynamic) with depth satisfies the hypotheses of § 10.3.2

  b) the underground structure has a limited depth, in order to fulfil the conditions for the development of earthquake earth pressures according to **§ 10.3.2**

11.4.1 GROUND SHAKING

- **(3)** **Large underground structures** subjected to seismic shaking may be analyzed using a two–dimensional (2D) **frame-spring model**
- **Annex I** provides specifications for such an analysis
- **(4)** The **seismic loads may be introduced statically**, applying an equivalent inertial force induced by the maximum ground acceleration or equivalent ground displacement at the individual **springs**, both calculated under free-field conditions from a site response analysis
- **Annex I** provides guidance for approximate estimates of **strain compatible soil springs**

11.4.1 GROUND SHAKING

- **Annex I** provides guidance for approximate estimates of strain compatible soil springs

  These estimates can only be **used for rather shallow structures** with depth not exceeding 10-15 m

  For deeper structures, the use of spring expressions provided in **Annex I** can lead to large uncertainties and differences in the calculated internal forces

11.4.1 GROUND SHAKING

- **(5)** For **underground structures in high seismic action classes, full dynamic time history 2D or 3D analysis of the coupled soil-structure system**

  Ground and structure properties should be simulated in a wide range of strains

11.4.2 PERMANENT GROUND DISPLACEMENTS

- **Large underground structures can not accommodate moderate to large permanent ground displacements due to seismic fault failure**

- Best strategy for seismic design is to relocate these structures far from the fault offset

- **(1)** For **very stiff structures crossing a fault, § 7.1.2** may be applied

11.5 CULVERTS

11.5 CULVERTS

- Typical structures (rigid-flexible) in transportation and hydraulic networks generally of short length and dimensions
- Consider the seismic response of the ground, the embankment and earth fill in which they are embedded
- Culverts are particularly vulnerable to permanent ground deformations!
- Effects of transient ground shaking may be neglected for culverts, of any shape and typology, with less than 2,0 m span and may be designed according to § 11.1 to § 11.3 for large dimension culverts
- Design of **joints of segmental culverts**: Provide enough deformation capacity in tension and compression to withstand transient and permanent longitudinal ground displacements

THANK YOU FOR YOUR ATTENTION