Performance-based design of energy geostructures

Prof. Lyesse Laloui

EPFL

Swiss Federal Institute of Technology in Lausanne
Laboratory of Soil Mechanics

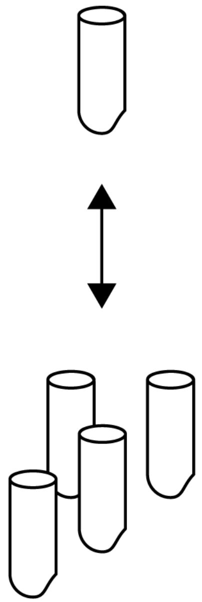
The Eurocode Programme

European norm code	European norm title
EN 1990	Eurocode: Basis of Structural Design
EN 1991	Eurocode 1: Actions on Structures
EN 1992	Eurocode 2: Design of Concrete Structures
EN 1993	Eurocode 3: Design of Steel Structures
EN 1994	Eurocode 4: Design of Composite Steel and Concrete Structures
EN 1995	Eurocode 5: Design of Timber Structures
EN 1996	Eurocode 6: Design of Masonry Structures
EN 1997	Eurocode 7: Geotechnical Design
EN 1998	Eurocode 8: Design of Structures for Earthquake Resistance
EN 1999	Eurocode 9: Design of Aluminium Structures

Proposed performance-based design approach

ULTIMATE LIMIT STATES DESIGN

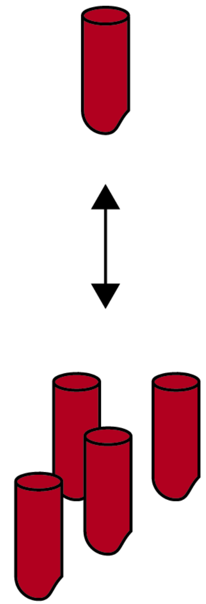
Conventional approach



(i) single and group bearing capacity estimation;
(ii) bending verification;
(iii) shear and punching shear verification;

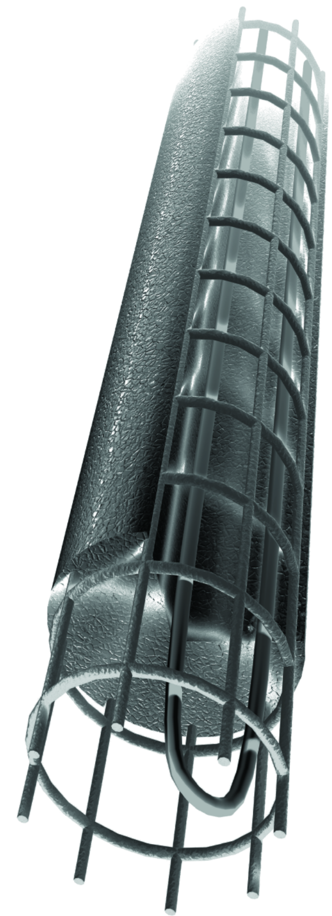
SERVICEABILITY LIMIT STATES DESIGN

Modified approach



(i) single and group vertical displacement limitation;
(ii) deflection and angular distortion control;
(iii) compressive stress limitation;
(iv) tensile stress limitation;
(v) crack control

APPLICATION



EN 1990 statement

“Thermal effects should be considered for ultimate limit states only where they are significant (e.g., fatigue conditions, […] second order effects […]).

In other cases, they need not be considered, provided that the <u>ductility</u> and <u>rotation</u> capacity of the elements are sufficient.”

Proposed geotechnical and structural design approach

1. **Geotechnical ultimate limit states:**
   - Bearing capacity estimation for single and group of energy piles

2. **Structural ultimate limit states:**
   - Verification of cross-section of reinforced concrete under compression and/or tension

- **NOTE: calculations performed in a conventional way, i.e., discounting the geothermal operation of the energy piles**

Combinations of actions: ultimate limit states

- **Persistent and transient design situations (ULS GEO & STR)**
- Fundamental combination of design effects ($\gamma_i \geq 1,\ \psi_i \leq 1$)

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j} + \gamma_P P + \gamma_{Q,1} Q_{k,1} + \sum_{i\geq 1} \gamma_{Q,i} \psi_{0,i} Q_{k,i}$$

Ductility-oriented design approach

- To ensure adequate ductility capacity of reinforced concrete members:

    i. the resisting axial force of the cross-sections needs to be greater than or equal to the axial force needed to crack them in view of potential strain localisation effects

    ii. the reinforcement has to be characterised by a large deformation capacity

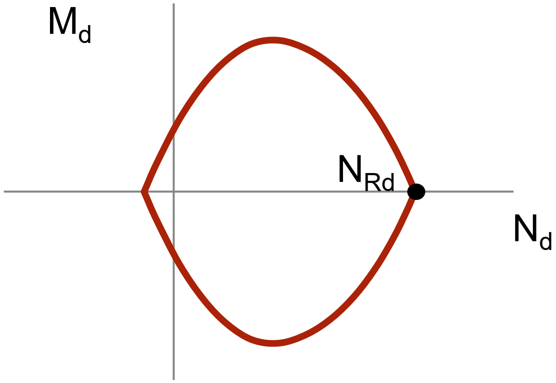
    iii. the ratio f_t/f_y has to respect a lower bound

(Rotta Loria et al., 2020)

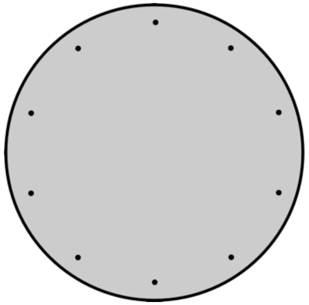
Key aspects to consider

- **Two aspects to consider for an appropriate design that does not exceed structural ultimate limit states:**

1. $$N_{Rd} \geq Q_{ud}$$



2. $$\rho_r = \rho_{r,min} \geq \frac{f_{ct}}{f_y}$$



(Rotta Loria et al., 2020)

Proposed geotechnical and structural design approach

1. **Geotechnical serviceability limit states:**

   - Analysis of the vertical displacement of single and group of energy piles subjected to mechanical and thermal loads

2. **Structural serviceability limit states:**

   - Compressive stress limitation in concrete
   - Tensile stress limitation
   - Crack control
   - Deflection control

- **NOTE: calculations performed in an innovative way, i.e., considering the geothermal operation of the energy piles**

Combinations of actions: serviceability limit states

- Characteristic combination of design effects ($\gamma_i = 1,\ \psi_i \leq 1$)

$$\sum_{j\geq 1} G_{k,j} + P + Q_{k,1} + \sum_{i\geq 1} \psi_{0,i} Q_{k,i}$$

- Frequent combination of design effects ($\gamma_i = 1,\ \psi_i \leq 1$)

$$\sum_{j\geq 1} G_{k,j} + P + \psi_{1,1} Q_{k,1} + \sum_{i\geq 1} \psi_{2,i} Q_{k,i}$$

- Quasi-permanent combination of design effects ($\gamma_i = 1,\ \psi_i \leq 1$)

$$\sum_{j\geq 1} G_{k,j} + P + \sum_{i\geq 1} \psi_{2,i} Q_{k,i}$$

What are thermal actions for energy geostructures?

- Variable actions because related to the aleatory and varied nature of the conditions and factors that characterise the outer environment, and/or the interaction between the outer and inner environments
- Indirect actions because resulting from boundary loads that cause a temperature change
- Free actions because characterised by an intrinsic variable distribution in space
- Static actions because generally not involving accelerations

Partial factors for thermal actions

Rotta Loria, A. F., Bocco, M., Garbellini, C., Muttoni, A. and Laloui, L. (2020) The role of thermal loads in the performance-based design of energy piles. Geomechanics for Energy and the Environment. Under review.

$$\psi_0 = 0.6$$

$$\psi_1 = 0.5$$

$$\psi_2 = 0.5$$

(Rotta Loria et al., 2020)

Thermal loads do not involve ultimate limit states

- **The geothermal operation of energy geostructures does not involve ultimate limit states, but only serviceability limit states**

- **Thermal loads applied to energy geostructures are deformation-related problems, not failure-related problems**

- **A ductile behaviour of the reinforced concrete cross-sections is essential**

Considerations for analysis and design

- **Provided that a ductility-oriented design approach is ensured, the design of energy geostructures can be considered**

  - **At ULS: a conventional design process against the combined action of only mechanical loads**

  - **At SLS: a modified design process against the combined action of both mechanical and thermal loads**