Performance-based design of energy geostructures

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Outline

- Available design recommendations and standards
- Performance-based design in the framework of *Eurocodes*
- Performance-based design of energy geostructures

Recall: typical aspects to consider in design

Short-term

Mechanical performance

Geotechnical and structural behaviour:

- **Stress in the ground structure**
- **Displacement of the ground structure**

Thermally and mechanically induced effects on soil behaviour

Thermally and mechanically induced effects on soil-structure interaction

Thermal performance

Energy behaviour:

- **Thermal power extracted and/or injected from and into the ground**

Time constants

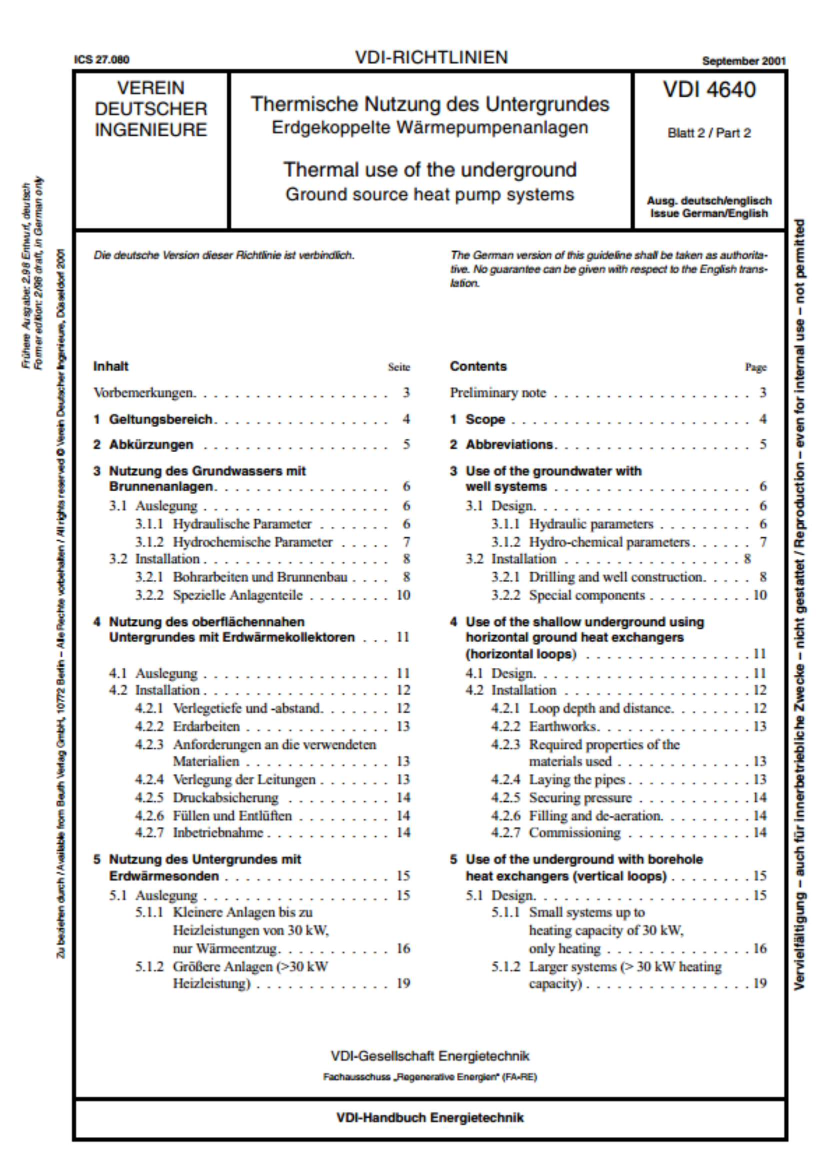
Thermal recharging of ground

Storage potential of ground

Long-term

Available design recommendations and standards

- Documentation VDI 4640, entitled «Thermische nutzung des untergrundes erdgekoppelte wärmepumpenanlagen» (Thermal use of the underground: ground source heat pump systems)
- Authors: Verein Deutscher Ingenieure (German Association of Engineers)
- First norm in which energy geostructures are considered (2001)
- No information about the geotechnical and structural design but only about the energy design


ICS 27.080 VDI-RICHTLINIEN September 2001

VEREIN DEUTSCHER INGENIEURE

Thermische Nutzung des Untergrundes
Erdgekoppelte Wärmepumpenanlagen

Thermal use of the underground
Ground source heat pump systems

VDI 4640
Blatt 2 / Part 2

Ausg. deutsch/englisch
Issue German/English

Die deutsche Version dieser Richtlinie ist verbindlich.

The German version of this guideline shall be taken as authoritative. No guarantee can be given with respect to the English translation.

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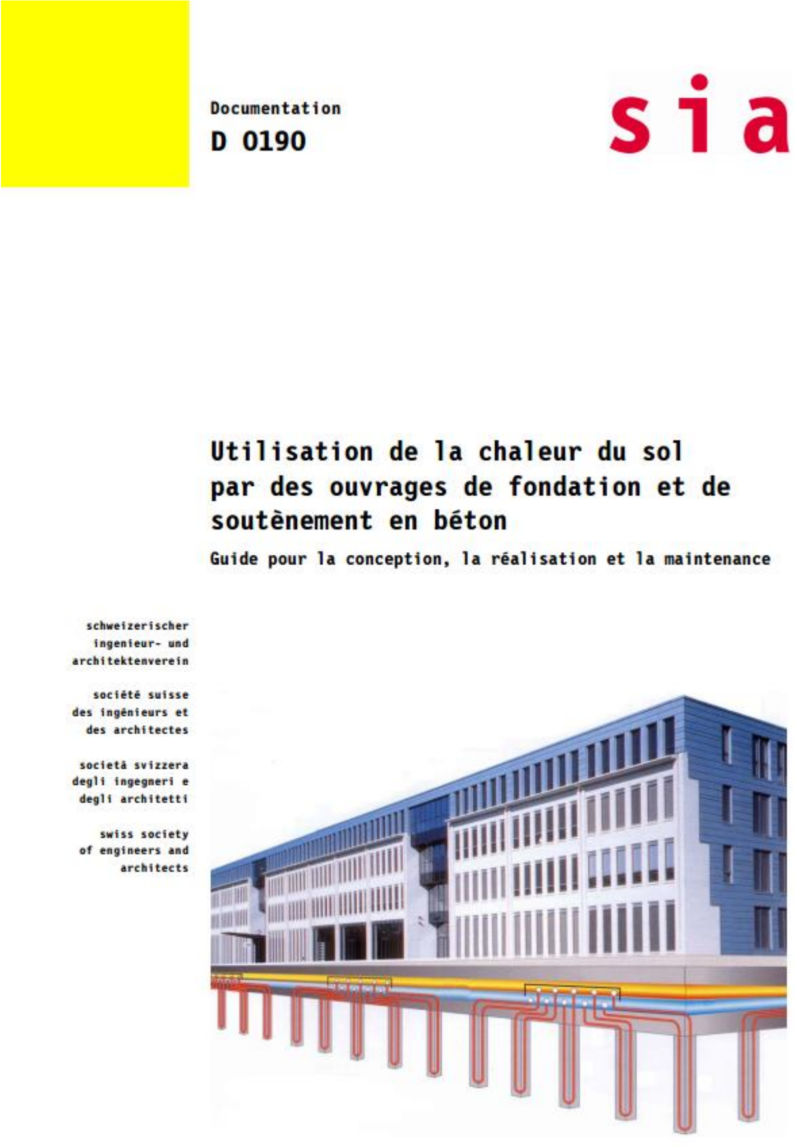
VDI-Gesellschaft Energietechnik
Fachausschuss „Regenerative Energien" (FA-RE)

VDI-Handbuch Energietechnik

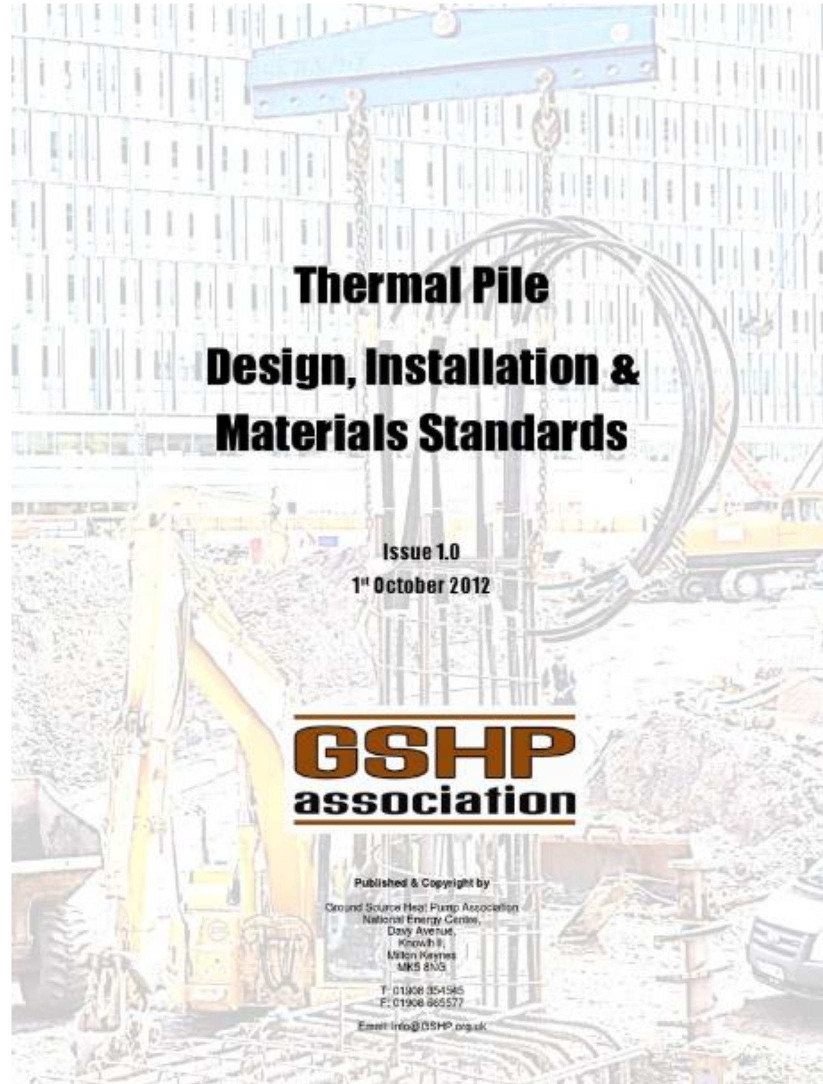
Towards a design approach for energy geostructures

- Documentation SIA D 0190, entitled «Utilisation de la chaleur du sol par des ouvrages de fondation et de soutènement en béton. Guide pour la conception, la réalisation et la maintenance»
- Authors: Société Suisse des Ingénieurs et des Architectes
- First contribution towards a rational geotechnical and structural design (in addition to the energy design) of energy geostructures (2005)



Towards a design approach for energy geostructures

- TPS Documentation, entitled «Thermal pile design, installation and material standards»
- Authors: Ground Source Heat Pump Association National Energy Centre (UK)
- Includes additional information about the geotechnical and structural design of energy *piles* (2012)



Towards a design approach for energy geostructures

- «Recommendations pour la conception, le dimensionnement te la mise en œuvre des géostructures thermiques»
- Authors: Comité Français de la Mécanique des Sols et de Géotechnique
- Latest recomendations for the geotechnical and structural design and applications of energy geostructures (2017)

Version 1 Janvier 2017

Recommandations pour la conception, le dimensionnement et la mise en œuvre des géostructures thermiques

CFMS/SYNTEC INGENIERIE/SOFFONS-FNTP

Illustration : géothermie-professionnelle

CFMS

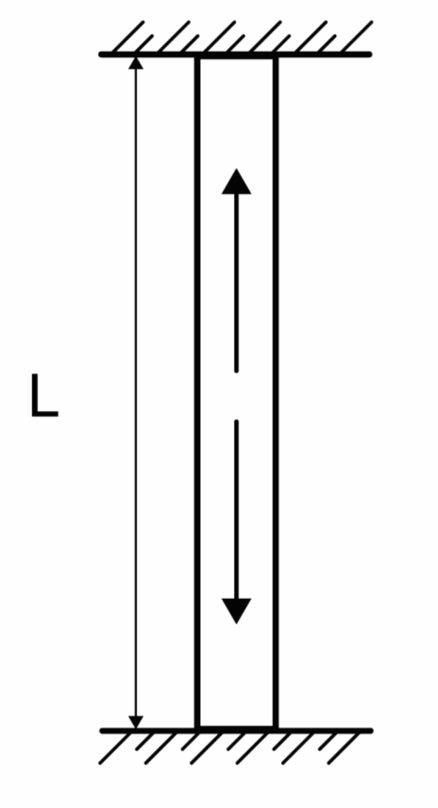
SYNTEC-INGÉNIERIE

Features of recommendations 1, 2 and 3

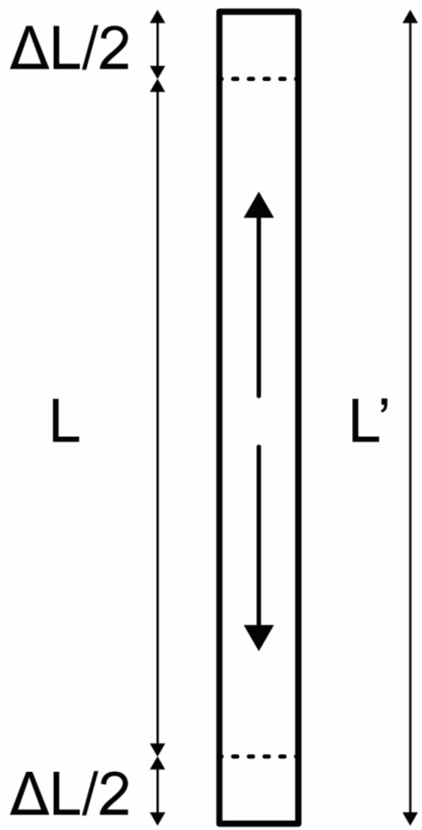
- Advantages:
  - Provide indications for an effective energy design and application of energy geostructures
- Disadvantages (geotechnical and structural design):
  - Limited to problems involving energy piles
  - Applicable to a limited number of design situations
  - Involve in most cases an oversizing of the structure because based on worst-case scenario considerations

Comments: UK standards

- Thermally induced stress may be checked under completely restrained conditions



- Thermally induced displacement may be calculated under free expansion conditions



(Laloui and Rotta Loria, 2019)

Comments: UK standards

- **According to the TPS, the thermally induced stress associated with completely restrained conditions may be considered as an additional force applied at the pile toe**

- *This would involve a lengthening of the energy piles*

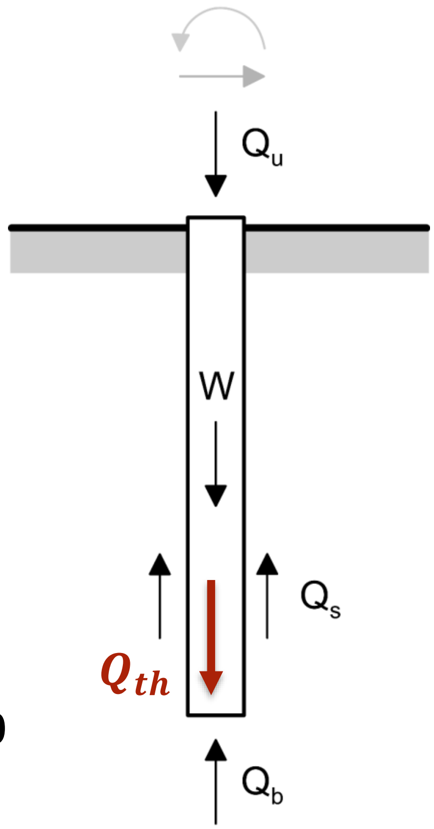
  - Conventional capacity calculation

$$Q_u = Q_s + Q_b - W$$

  - Revised capacity calculation

$$Q_u = Q_s + Q_b - W - \boldsymbol{Q_{th}}$$

  - $\boldsymbol{Q_{th}} =$ Thermally induced force applied at pile b



(Laloui and Rotta Loria, 2019)

Drawbacks

- Pile lengthening is conservative for failure-related verifications against mechanical loads
    - A greater pile length results in a greater bearing capacity
- However, pile lengthening is NOT conservative for deformation-related verifications against thermal loads
    - A greater pile length results in greater thermally induced displacements for the same applied temperature change

Illustrative example

- Consider an energy pile subjected to a $\Delta T = 10\ °\text{C}$ and by a $\alpha_{EP} = 10\ \mu\varepsilon/°\text{C}$ under free expansion conditions

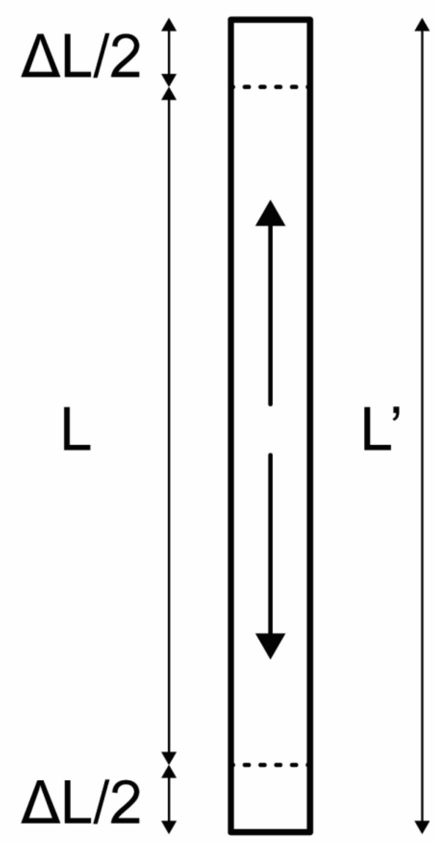
- The thermally induced strain, for no matter which kind of pile length, will be:

$$\varepsilon_f^{th} = -\alpha_{EP}\Delta T = 100\ \mu\varepsilon$$

- However, if the pile length is $L = 10$ m or $L = 20$ m, the variation in length will be

$$\Delta L_1 = -\varepsilon_f^{th} L = \alpha_{EP}\Delta T L = 1 \text{ mm}$$

$$\Delta L_2 = -\varepsilon_f^{th} L = \alpha_{EP}\Delta T L = 2 \text{ mm}$$



(Laloui and Rotta Loria, 2019)

Further comments

- When considering the effects of thermal loads
    - Considering the pile completely blocked leads to excessively high values of thermally induced stress
    - Considering the pile completely free represents a situation excessively far from reality and does not account for the real physics of pile groups (group effects)

Features of recommendations 4

- **The most comprehensive recommendations available**

- Advantages:
    - Provide indications for an effective energy design and practical application of energy geostructures
    - Consider a performance-based design approach

Features of recommendations 4

- Remarks with respect to the suggested approach to consider the influence of thermal loads:
    - Propose to carry out both failure- and deformation-related verifications including the effects of thermal actions
        - **RMK: thermal actions applied to energy geostructures represent a deformation-related problem, not a failure-related problem**
    - Provide partial factors for thermal actions
        - **RMK: different values may be considered nationally**

Performance-based design in the framework of Eurocodes

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

Limit states

- Limit states are the states whose achievement involves the loss of functioning or required performance for a designed structure

- Distinction shall be made between two limit states (EN 1990):

  - **Ultimate limit states**: associated with the collapse or failure of the structure or components and thus involving the safety of people.

  - **Serviceability limit states**: associated to the loss of functionality of a structure with reference to the requirements of its normal use, comfort, appearance and durability, and thus not involving the safety of people.

Actions

- Actions are sets of forces applied to the structure as well as sets of imposed deformations or accelerations

- The classification of actions based on time foresees:

    - Permanent actions, G: actions that are likely to act throughout a given reference period and for which the variation in magnitude with time is negligible

    - Variable actions, Q: actions whose variation in magnitude with time is neither negligible nor monotonic

    - Accidental actions, A: actions, usually of short duration but of significant magnitude, which are unlikely to occur on a given structure during the design working life

Examples of actions

Permanent actions	Variable actions	Accidental actions
Self-weight of structures, fittings and fixed equipment	Imposed deformations caused, e.g., by temperature changes	Seismic actions
Prestressing forces	Imposed loads on building floors, beams and roofs	Explosions
Water and earth loads	Wind actions*	Impacts from vehicles
Actions caused by shrinkage	Snow loads*	

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

Verifications of requirements through partial factor method

- **The actions and resistances governing the performance of structures are aleatory variables**

- **The aleatory character of actions and resistances in design of structures are tackled in Eurocodes through a semi-probabilistic safety framework and an associated partial factor approach**

- **This approach is termed *performance-based design approach***

Conventional verification approach

- **In conventional deterministic design approaches, the uncertainties are treated by applying a unique safety factor, $\boldsymbol{F_s}$**

$$F_s = \frac{R}{E} = 2.5 - 3$$

- where:
  - R = resistance value
  - E = action or effect of action value

Partial factor method verification approach

- **In this approach the uncertainties of the variables are treated right at the sources by introducing partial safety factors, γ_i**

- **Four are the key variables:**

  - **Actions, F**
  - **Effects of actions, E**
  - **Material properties, X**
  - **Resistances, R**

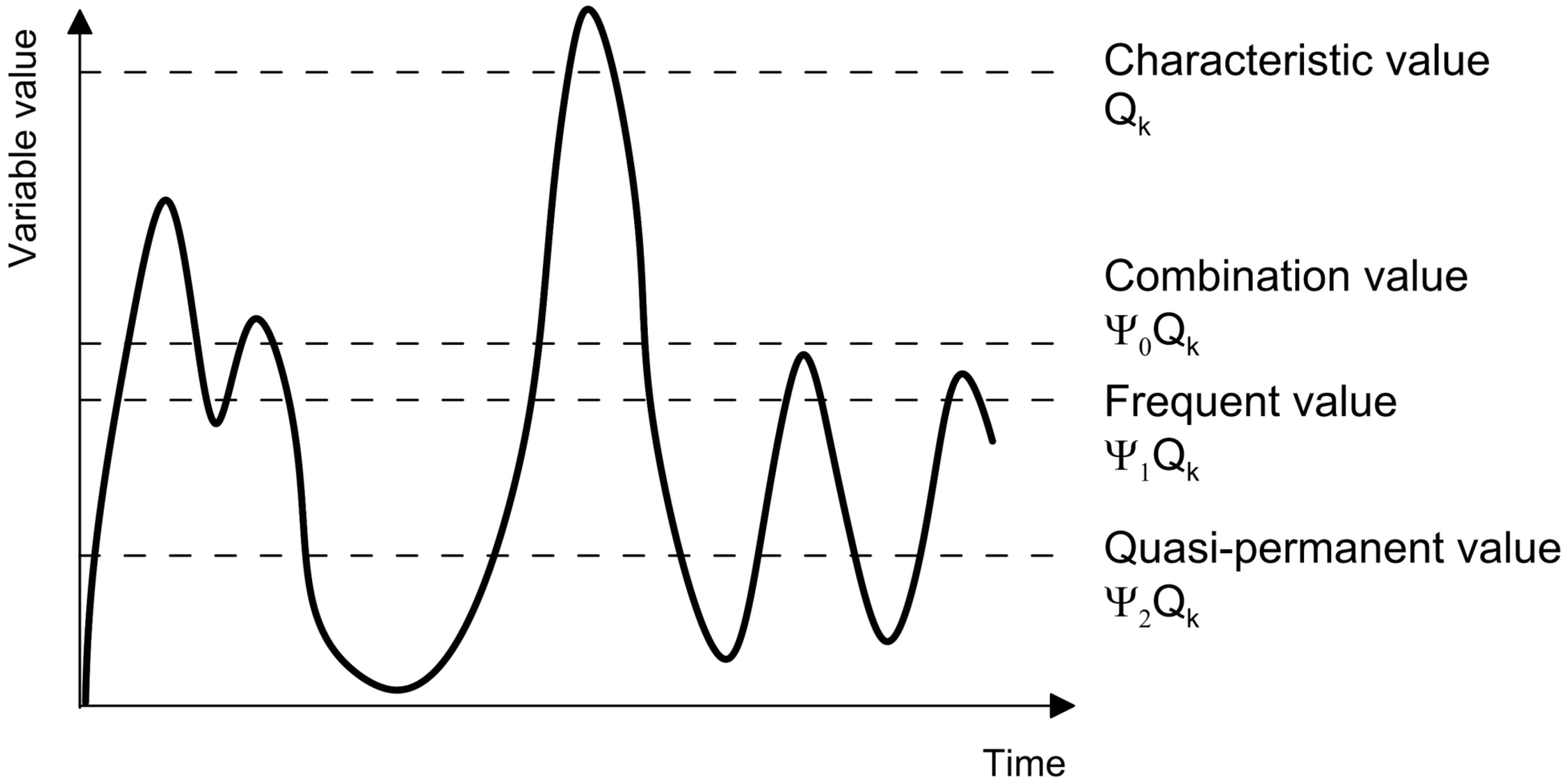
$$E_d = E\{\gamma_{F,i} F_{rep,i}; \frac{X_{k,i}}{\gamma_{M,i}}; a_d\}, \text{ with } i \geq 1$$

$$R_d = R\{\gamma_{F,i} F_{rep,i}; \frac{X_{k,i}}{\gamma_{M,i}}; a_d\}, \text{ with } i \geq 1$$

Actions and effects of actions

- **The representative values of actions $F_{rep,i}$ may be**
    - **Characteristic values of actions $F_{k,i}$:** the main representative value of the action
    - **Accompanying values of actions $\psi_i F_{k,i}$** (where ψ_i are combination factors) for variable actions
        - They account for the probability of a simultaneous occurrence of these actions in specific situations referred to the design working life of the structure

Accompanying values of actions



(Laloui and Rotta Loria, 2018)

Performance-based design

- The prescription (e.g., inequality) that shall be verified when considering a limit state of rupture or failure of a section, member, connection or medium, i.e., an ultimate limit state, is (EN 1990)

$$E_d \leq R_d$$

- The prescription (e.g., inequality) that shall be verified when considering a limit state of loss of functionality of a section, member, connection or medium, i.e., a serviceability limit state, is (EN 1990)

$$E_d \leq C_d$$

  - where C_d = design value of the relevant serviceability criterion

Combinations of actions: ultimate limit states

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

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

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 ($\gamma_i = 1,\ \psi_i \leq 1$)

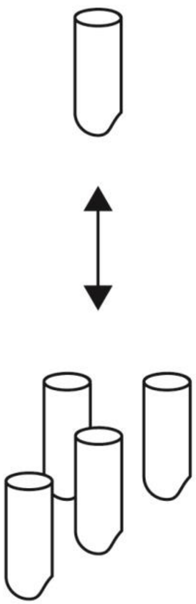
$$\sum_{j\geq 1} G_{k,j} + P + \sum_{i\geq 1} \psi_{2,i} Q_{k,i}$$

Performance-based design of energy geostructures

Proposed performance-based design approach

ULTIMATE LIMIT STATES DESIGN

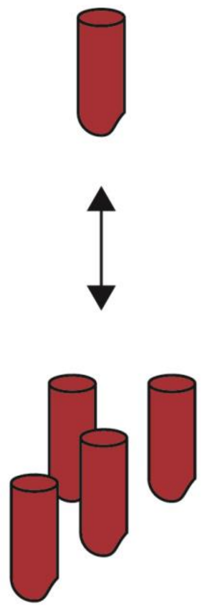
Conventional approach



(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."

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**

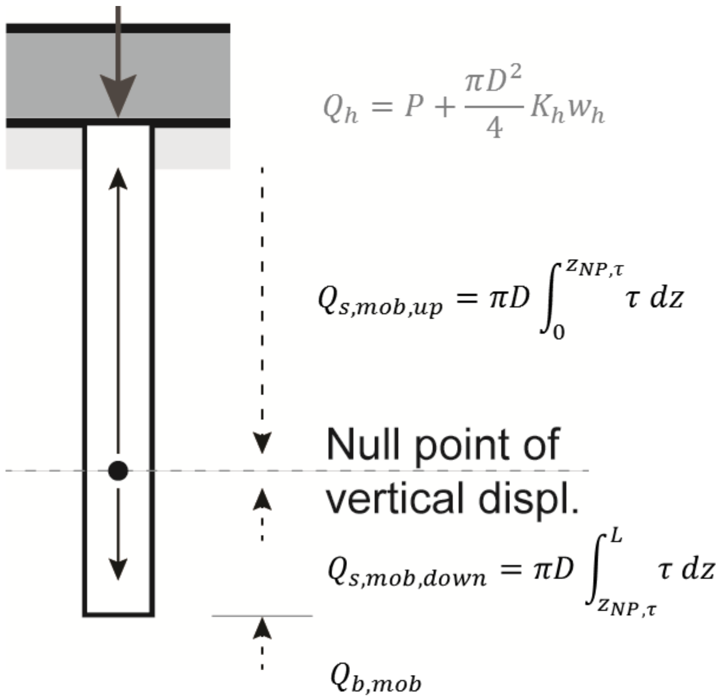
- **Thermal loads applied to energy geostructures are deformation-related problems, not failure-related problems**

- **If an energy geostructure would fail because of the applied thermal loads, an inappropriate design would have already been carried out with regards to mechanical loads**

Proof of approach validity for piles

- The presence of the null point will always ensure equilibrium and prevent the formation of a geotechnical collapse mechanism

$$Q_h + Q_{s,mob,a} + Q_{s,mob,b} + Q_{b,mob} = 0$$



(Rotta Loria et al., 2020)

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

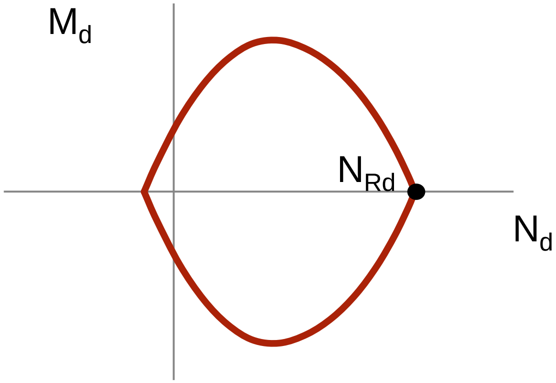
  iii. the ratio f_t/f_y has to respect a lower bound

(Rotta Loria et al., 2020)

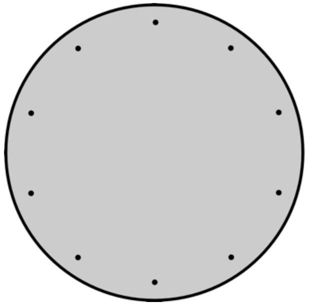
Key aspects to consider

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

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



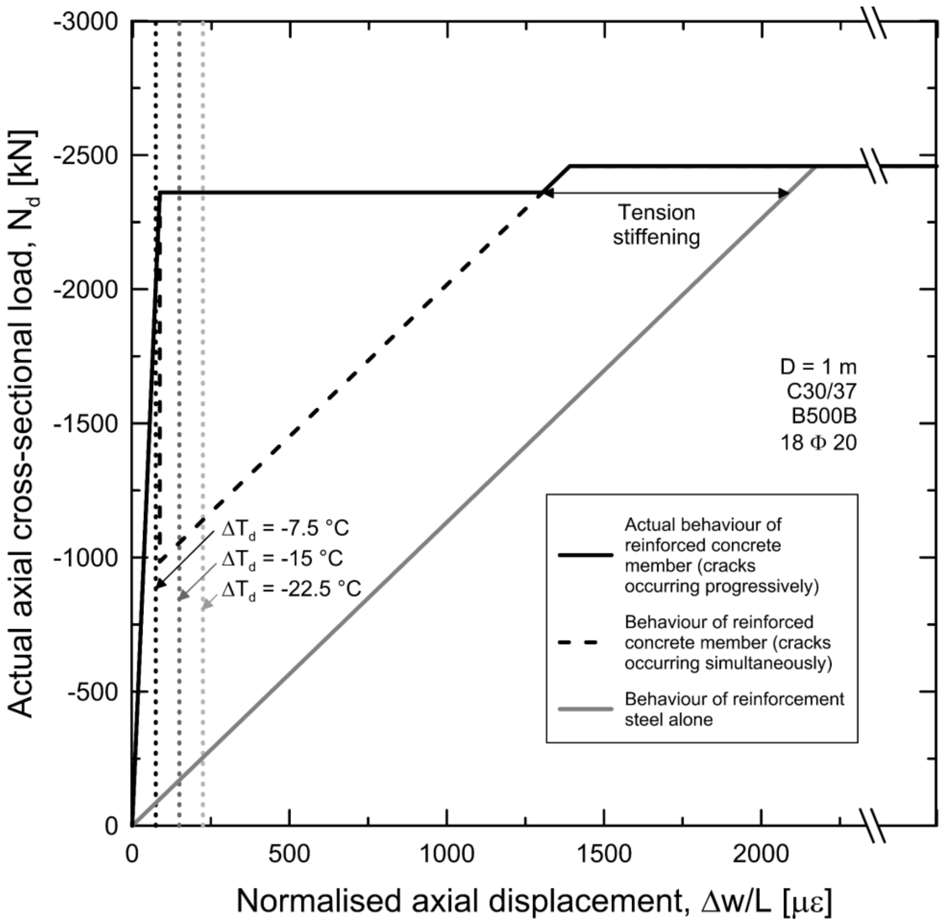
2. $$\rho_r = \rho_{r,min} \geq \frac{f_{ct}}{f_y}$$



(Rotta Loria et al., 2020)

Proof of approach validity for piles

- A ductility-oriented design approach will always prevent from structural ultimate limit states to be exceeded



(Rotta Loria et al., 2020)

Partial factors for thermal actions

Rotta Loria, A. F., Bocco, M., Garbellini, C., Muttoni, A. and Laloui, L. (2018) The role of thermal loads in the performance-based design of energy piles. Geomechanics for Energy and the Environment. Under review.

$$\psi_0 = 0.6$$

$$\psi_1 = 0.5$$

$$\psi_2 = 0.5$$

Cfms-Syntec-Soffons-Fntp (2017) Recommandations pour la conception, le dimensionnement et la mise en œuvre des géostructures thermiques.

$$\psi_0 = 0.6$$

$$\psi_1 = 0.5$$

$$\psi_2 = 0.2$$

(Rotta Loria et al., 2020)

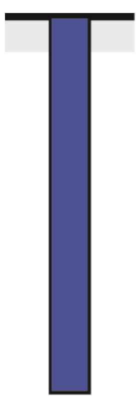
Example: characteristic combination

Thermal load is the dominant variable action

$$E_d = \sum_{j\geq 1} G_{k,j} + \Delta T_k + \psi_{0,2} Q_{k,2} + \cdots + \psi_{0,i} Q_{k,i}$$

Thermal load is not the dominant variable action

$$E_d = \sum_{j\geq 1} G_{k,j} + Q_{k,1} + \psi_{0,2} \Delta T_k + \cdots + \psi_{0,i} Q_{k,i}$$



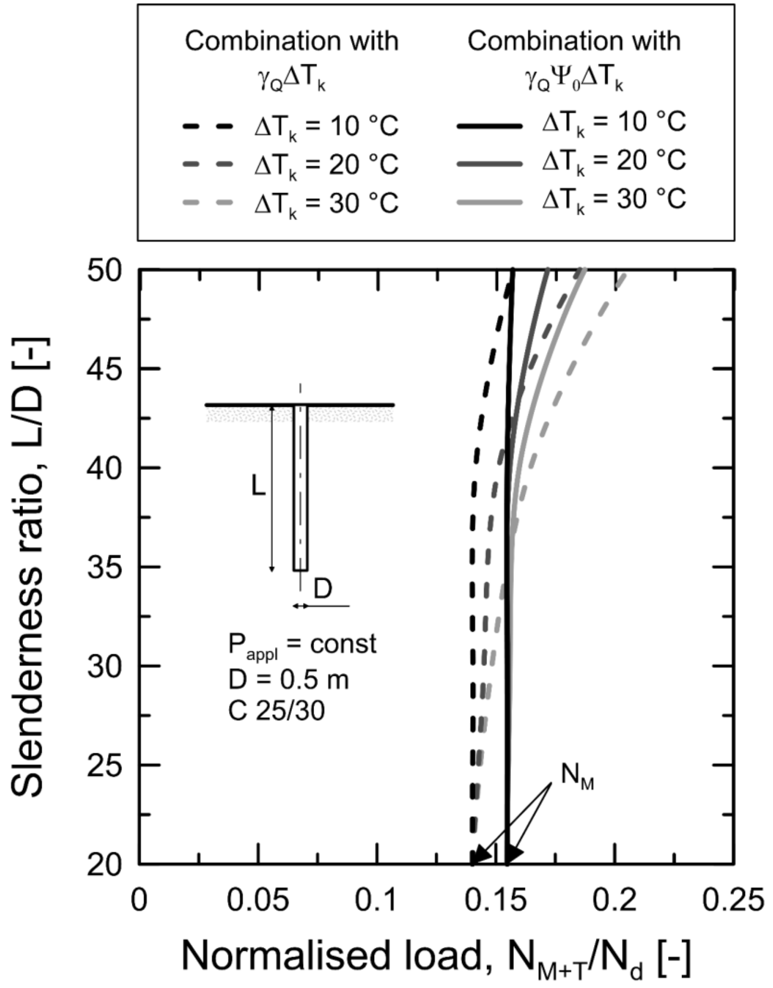
$$E_d = \sum_{j\geq 1} G_{k,j} + \Delta T_k + \psi_{0,2} Q_{k,i} + \cdots + \psi_{0,i} Q_{k,i}$$

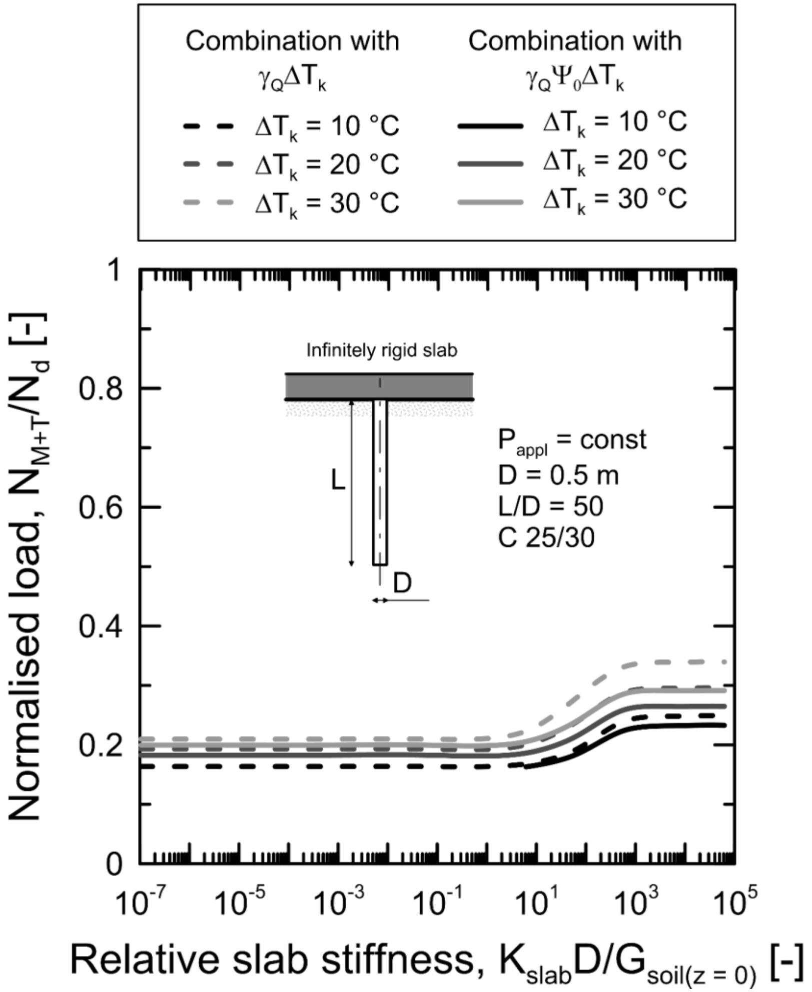
(Rotta Loria et al., 2020)

Orders of magnitude

(Rotta Loria et al., 2020)

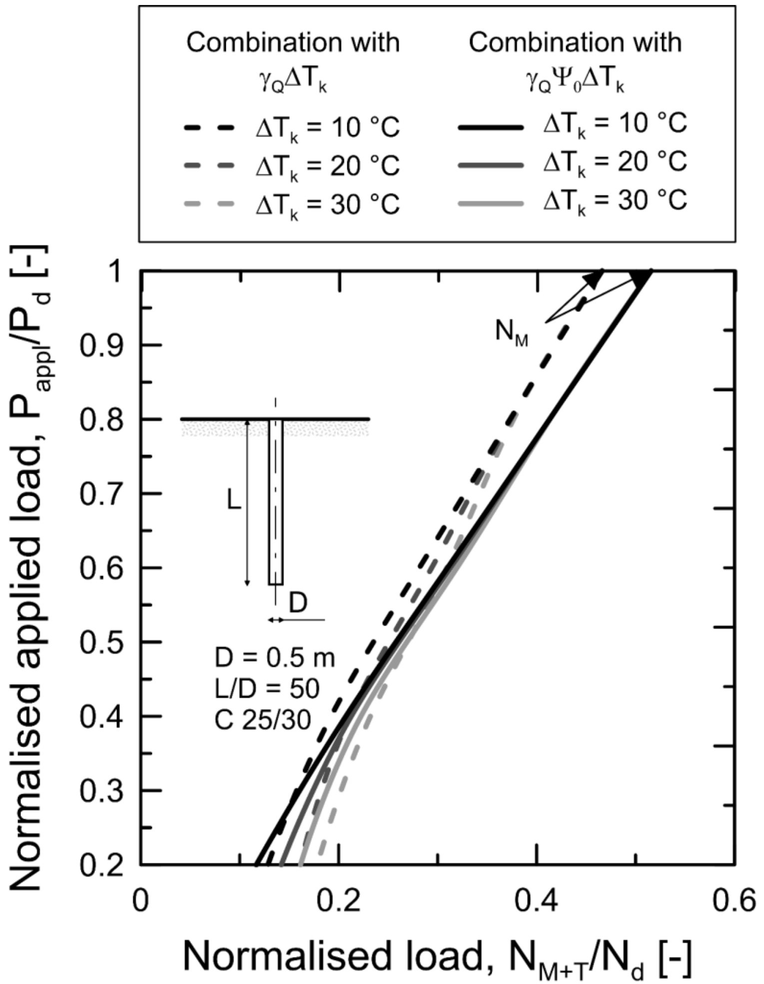
- Piles dimensioned for a mechanical load and then lengthened

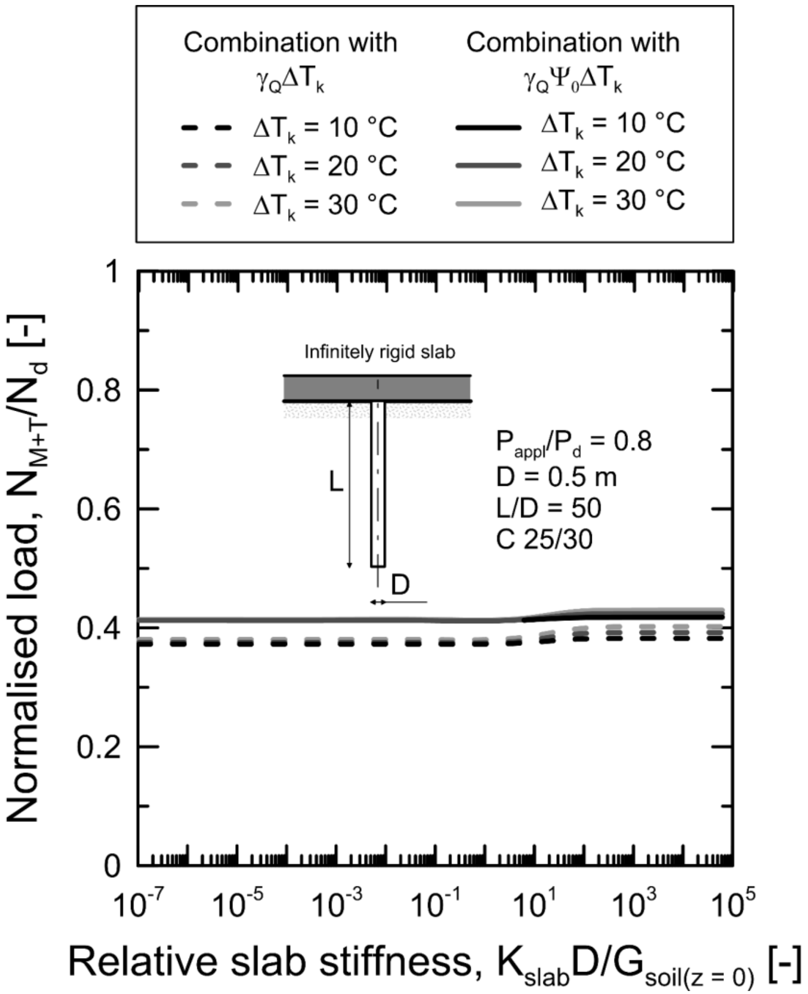




(Rotta Loria et al., 2020)

- Piles dimensioned based on the most loaded pile in a group and carrying a lower load compared to their ultimate capacity





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**

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**

Summary and concluding remarks

Considerations for analysis and design

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

- **If, in addition to avoiding stability problems, sufficient ductility capacity is ensured, imposed deformations can be neglected**

- **They are absorbed by the structure (development of the "auto-stress state")**

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**