NAME ______________________________

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Instructions

The questions include multiple choice questions and open questions covering theoretical and applied problems that have been treated during the course.

Exam questions

1. The stress unit of the metric system is:
    a. Gram, g
    b. Newton, N
    c. Pascal, Pa
    d. None of the above

2. The strain unit is:
    a. Meter, m
    b. Newton, N
    c. Pascal, Pa
    d. None of the above

3. What are the two fundamental roles of energy geostructures? What is the main difference between energy and conventional geostructures?

    To couple the role of the structural support with that of the geothermal heat exchanger. Conventional geostructures serve only for the former role.

4. In general, shallow geothermal systems can be exploited:
    a. To produce heat and electrical power
    b. To produce power
    c. To produce heat
    d. None of the above

5. List and describe the purpose of the possible applications of energy piles.

    Heat extraction: heat is extracted in the cool season to heat the superstructure, cooling the energy geostructure;

Heat injection: heat is injected in the warm season to cool the superstructure, heating the energy geostructure;
Heat extraction and heat injection: heat is extracted in the cool season to heat the superstructure and injected in the warm season to cool the superstructure, cooling and heating the energy geostructure, respectively;
Heat injection for storage purposes: heat (usually arising from thermal solar panels) is injected (usually during the warm period) for a successive use of the superstructure (usually during the cool periods), heating the energy geostructure.

6. When an energy geostructure is cooled as a consequence of its geothermal operation, the building is:
    a. Cooled
    b. Heated
    c. Heated and cooled
    d. None of the above

7. The purpose of using a heat pump to heat a building environment through energy geostructures is:
    a. To enhance the heat input that can be extracted from the soil
    b. To diminish the heat input that can be extracted from the soil

8. The typical range of power for a heat extraction with heat pump application is
    a. 50-100 W/m
    b. 40-60 W/m
    c. 20-40 W/m

9. What are three of the typical aspects that need to be considered for the holistic, integrated, energy, geotechnical and structural design of energy geostructures?

    Stress in the ground structure;
    Displacement of the ground structure;
    Thermal power extracted and/or injected from and in the ground.

10. Which are the typical conditions or aspects that involve a stress variation in a body as a consequence of an applied temperature change?

    Stresses due to temperature changes in a body (thermally induced stresses) can arise as a consequence of external constraints, non-uniform temperature distribution or a combination of both of the above aspects.

11. Which are the two terms that govern the mathematical expression of the strain of a body subjected to a thermal load under free expansion conditions?

    The linear thermal expansion coefficient α and the applied temperature change ΔT.

12. The unit measure of the linear thermal expansion coefficient is:
    a. °C
    b. m/°C
    c. °C/m
    d. 1/°C

13. Considering a bar subjected to a temperature change in a completely restrained case:

    a. The thermally induced stress is zero
    b. The thermally induced displacement is zero
    c. None of the above

14. Consider a steel bar that is free to deform and subjected to a uniform temperature change. Is this bar characterised by a stress variation as a consequence of the applied temperature change?

    No, it is not.

15. How is the degree of freedom DOF of an energy pile mathematically defined? Specify the meaning of the terms involved in its definition.

    $$\boldsymbol{DOF = \frac{\varepsilon_o^{th}}{\varepsilon_f^{th}}}$$

    where ε_o^{th} is the observed strain and ε_f^{th} is the strain under free expansion conditions.

16. Write the mathematical expression of the thermally induced stress in an energy pile, with reference to a Young's modulus E, the observed strain ε_o^{th} and the free strain ε_f^{th}. Consider compressive stresses and contractive strains to be positive.

    $$\boldsymbol{\sigma_o^{th} = E\varepsilon_b^{th} = E\left(\varepsilon_o^{th} - \varepsilon_f^{th}\right) = E\left(\varepsilon_o^{th} + \alpha\Delta T\right)}$$

17. Calculate the deformation of a steel bar characterised by a linear thermal expansion coefficient of $\alpha = 12$ με/°C and subjected to a temperature change of $\Delta T = 20$ °C under free expansion conditions. Refer to one-dimensional conditions. Consider compressive stresses and contractive strains to be positive.

$$\boldsymbol{\varepsilon_f^{th} = -\alpha \Delta T = -240\ \mu\varepsilon}$$

18. Calculate the absolute value of thermally induced displacement of a steel bar of 20 m in length characterised by a linear thermal expansion coefficient of $\alpha = 12$ με/°C and subjected to a temperature change of $\Delta T = 20$ °C, assuming that the deformation of the bar is completely restrained at one end.

$$\boldsymbol{|\Delta L| = \left|\varepsilon_f^{th} L\right| = |-\alpha \Delta T L| = 4.8\ \text{mm}}$$

19. Calculate the stress that is generated in a completely restrained steel bar characterised by a linear thermal expansion coefficient of $\alpha = 12$ με/°C and Young's modulus of $E = 210$ GPa, subjected to a temperature change of $\Delta T = 20$ °C. Refer to one-dimensional conditions. Consider compressive stresses and contractive strains to be positive.

$$\boldsymbol{\sigma_r^{th} = E\varepsilon_b^{th} = E\alpha\Delta T = 50.4\ \text{MPa}}$$

20. What is the null point of an energy pile?
The null point is the setting of an energy pile characterised by zero thermally induced displacement, referring to one-dimensional conditions.

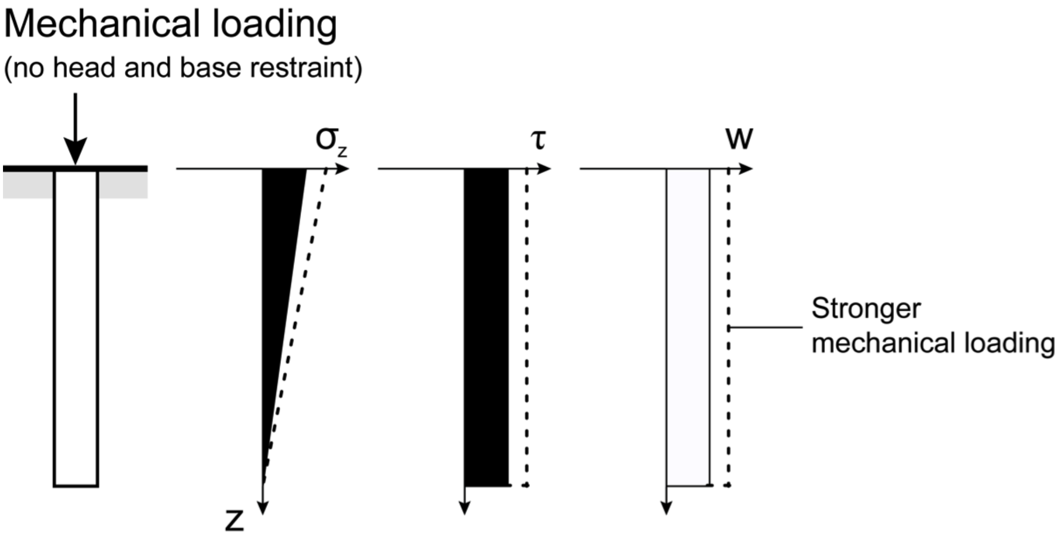
21. The presence of the null point in energy piles subjected to thermal loads involves that:
    - **a. Energy pile equilibrium cannot be solved via closed form solutions**
    - b. Energy pile equilibrium can be solved via closed form solutions
    - c. None of the above

22. The discussed thermo-mechanical schemes for energy piles are developed under the fundamental hypothesis of:
    - **a. (Thermo-)elastic conditions**
    - b. (Thermo-)plastic conditions
    - c. Anisotropic conditions
    - d. None of the above

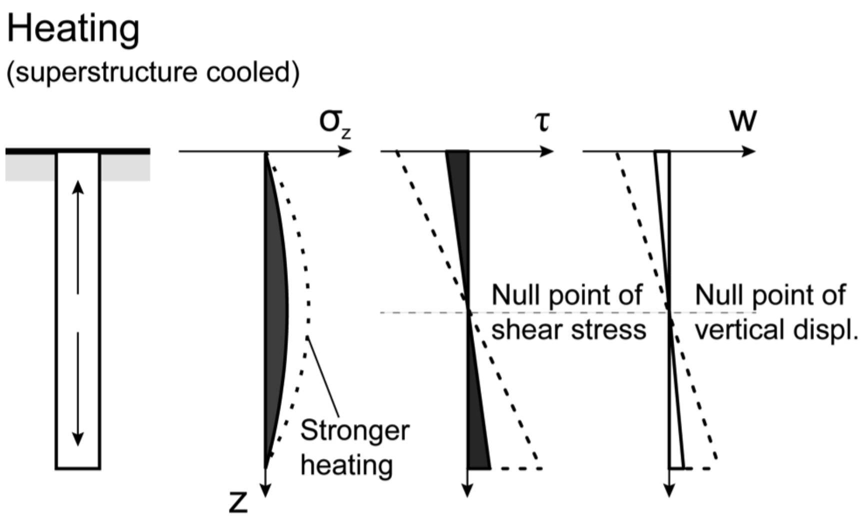
23. Can the superposition principle be employed to investigate the effects of the interactions caused by both mechanical and thermal loads among energy piles?

Yes, the superposition principle can be employed to investigate the effects of the interactions caused by both mechanical and thermal loads among energy piles. The reason for this is that, although the response of energy piles to mechanical and thermal loads is different, as soon as the loading conditions are reversible the superposition principle can be applied to analyse the displacement field caused by any type of loading (e.g., mechanical or thermal).

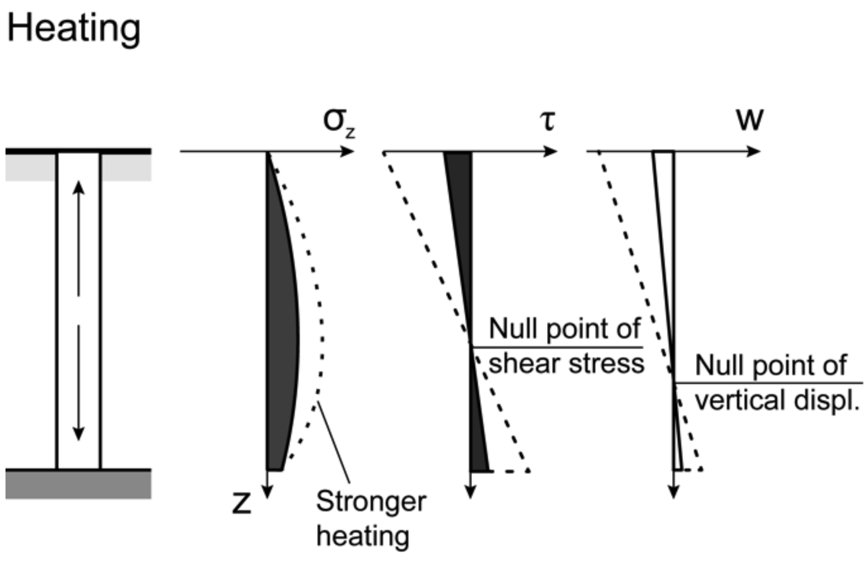
24. With reference to a thermo-elastic framework, sketch the vertical stress and vertical displacement variations caused by the application of a mechanical load at the head of an energy pile that is characterised by no head and base restraints (i.e., fully floating pile). Consider compressive stresses and downward displacements to be positive.



25. With reference to a thermo-elastic framework, sketch the vertical stress and vertical displacement variations caused by the application of a positive temperature change (heating thermal load) along an energy pile that is characterised by no head and base restraints (i.e., fully floating pile). Consider compressive stresses and downward displacements to be positive.



26. With reference to a thermo-elastic framework, sketch the vertical stress and vertical displacement variations caused by the application of a positive temperature change (heating thermal load) along an energy pile that is characterised by no head restraint but by a strong base restraint (i.e., end-bearing pile). Consider compressive stresses and downward displacements to be positive.



27. Which are the two basic methods that can be used to install piles?

Boring and driving.

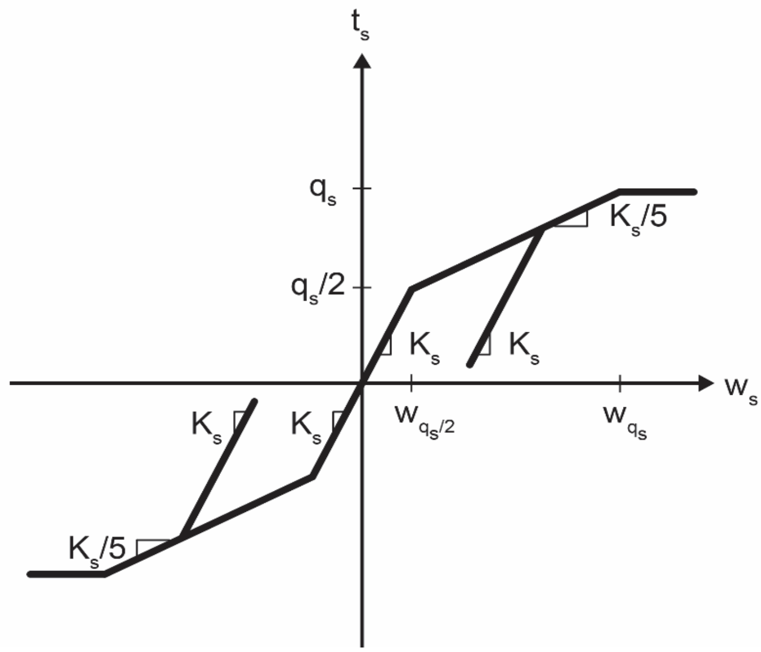
28. Write the vertical equilibrium equation that is accounted for characterising the ultimate load capacity of energy piles and specify the meaning of the involved terms.

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

where Q_s is the shaft capacity, Q_b is the base capacity and W is the weight of the pile.

29. Sketch the tri-linear load transfer curve *referring to energy piles* that has been proposed by Knellwolf et al. (2011), based on the work of Frank and Zhao (1982), and which describes the interaction between the pile shaft and the surrounding soil. Consider positive shear stresses developed with positive displacement values, i.e., settlements.

Load-transfer relationship for shaft of single isolated pile



30. Describe the physical meaning behind each of the three branches of the tri-linear load transfer curve *referring to energy piles* that has been proposed by Knellwolf et al. (2011), based on the work of Frank and Zhao (1982), and describes the interaction between the pile shaft and the surrounding soil.

First branch: linear elastic part characterising a reversible behaviour;
Second branch: linear plastic part characterising a partly reversible behaviour;
Third branch corresponding to a plateau: perfectly plastic part characterising an irreversible behaviour where displacement increases under constant load.

31. Describe the essential features of the load-transfer method for energy piles.

    Discretisation of the pile in a number of segments/elements to consider soil layers of different properties;

    Soil and pile properties remain constant with temperature but can be imposed to vary with depth;

    Soil and soil-pile interaction properties do not change with temperature;

    The relationships between the shaft friction-shaft displacement, head stress-head displacement and base-stress-base displacement are assumed to be known through load-transfer curves;

    Pile radial strains are neglected.

32. Which is the typical centre-to-centre spacing that distinguishes a closely spaced energy pile group from a widely spaced energy pile group, in terms of the pile diameter?

    $$\frac{s}{D} = 8$$

33. Which are the main effects of interactions on the behaviour of energy pile groups, in terms of deformation of the piles and stresses developed in the piles?

    The main effects of interactions of the behaviour of energy pile groups are increased group deformation and lower stress under the same average load applied in a situation where the pile can be considered to be single and isolated.

34. Does an analysis of an energy pile that is considered to be in a single and isolated case provide a conservative estimate of its displacement? Why?

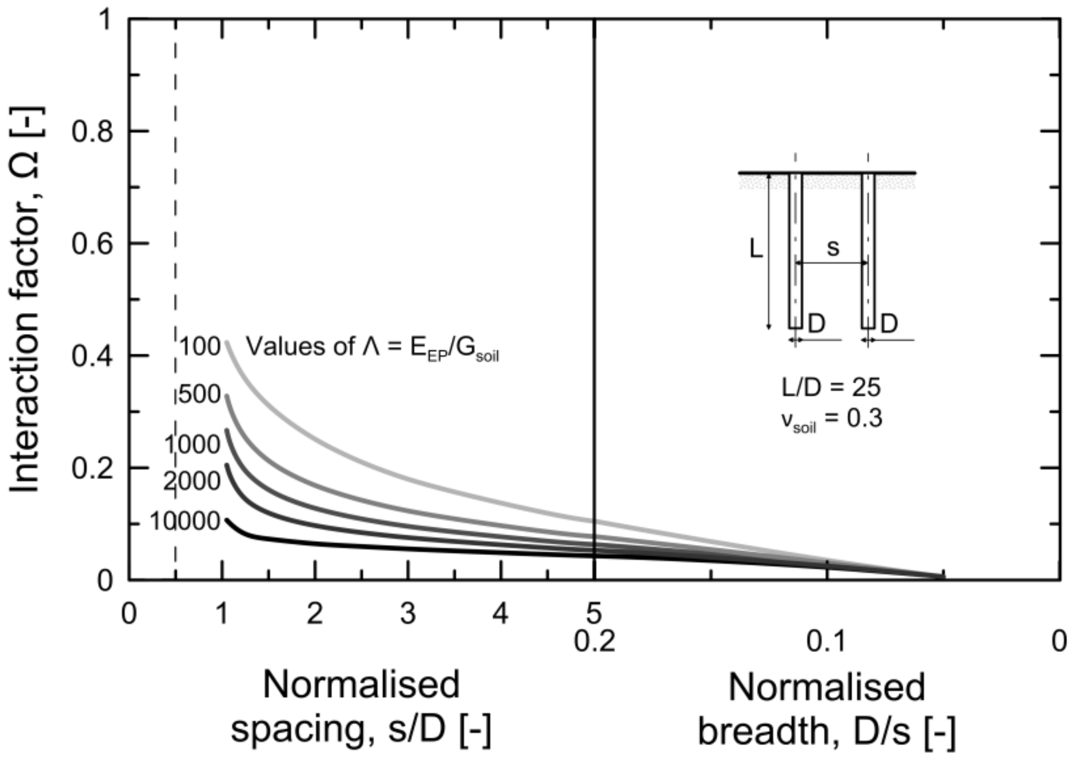
    No, it does not. The reason is because such an analysis neglected group effects, thus providing a lower estimate of the pile displacement.

35. How the displacement interaction factor is defined?

    $$\Omega = \frac{\text{additional displacement due to adjacent pile}}{\text{displacement of single isolated pile}} = \frac{w_j}{w_i}$$

36. Consider a group of two identical energy piles characterised by a slenderness ratio of $L/D = 25$ that are surrounded by an isotropic, homogeneous and deep thermo-elastic soil mass. Assume that one pile in the group is subjected to a temperature

change. If the piles are characterised by a Young's modulus of $E_{EP} = 30$ GPa and the soil by a Young's modulus of $E_{soil} = 78$ MPa and a Poisson's ratio of $\nu_{soil} = 0.3$, which is the value of interaction factor between the two piles for a normalised spacing of $s/D = 3$? Consider the following interaction factor chart to answer to this question.



Based on the available parameters, $G_{soil} = 30$ MPa, so $\Lambda = 1000$ and $\Omega \approx 0.1$.

37. Consider a group of two identical energy piles that are surrounded by an isotropic, homogeneous and deep thermo-elastic soil mass. Assume that both piles in the group are subjected to the same temperature change. Write the expression for the vertical displacement of each pile of the group w_k by considering that the vertical displacement of the piles in the single isolated case subjected to the same temperature change reads w_i and the interaction factor between the piles in the group is Ω.

$\boldsymbol{w_k = w_i(1 + \Omega)}$

38. Consider a square group of four identical energy piles subject to a $\Delta T = 15\ °C$. Assume that the vertical displacement per unit temperature change of the single isolated energy pile is $w_i = 0.122\ mm/°C$. The interaction factors for the two characteristic centre-to-centre distances between the piles are $\Omega_{s1} = 0.063$ and

$\Omega_{s2} = 0.045$. Which is the value of the average vertical head displacement of the group?

$$\boldsymbol{w_k = w_{ave} = w_1 + 2w_1 \Delta T \Omega_{s1} + w_1 \Delta T \Omega_{s2} = 2.14}$$

39. Which is the basic concept behind the equivalent pier method?

    The basic concept behind the equivalent pier method is that the mechanical behaviour of any energy pile group can be reproduced with sufficient accuracy for practical purposes by modelling the group as a single equivalent pier whose material properties are a homogenisation of those characterising the actual pile group. This pier will also need to be characterised by a modified load-transfer relationship compared to that of a single isolated pile to account for group effects and interaction between piles.

40. The equivalent pier method can be applied for aspect ratios of the group and for normalised spacing between the piles of
    - **a. AR < 4 and s/D ≤ 5**
    - **b.** AR > 4 and s/D ≤ 5
    - **c.** AR ≤ 4 and s/D >5
    - **d.** AR > 4 and s/D > 5

41. List the quantity/quantities that can be derived through the application of the equivalent pier method:

    Average displacement

42. What are the two typical aspects that govern the mechanical behaviour of the energy walls

    Bending and Frictional

43. To increase the thermal potential of energy walls it is better to install the pipes
    - a. Next to the ground
    - **b. It depends**
    - c. Next to the airside
    - d. None of the above

44. List the two fundamental modes of heat transfer for energy walls

    Conduction and convection

45. Discuss the advantages and disadvantages of the current available design recommendations and standards for energy geostructures?

    They provide indications for an effective energy design and application of energy geostructures. However, regarding the geotechnical and structural design they are limited to problems involving only energy piles and applicable to a limited number of design situations. In most cases they involve an oversizing of the structure because based on worst-case scenario considerations

46. Eurocodes are
    a. Prescriptive standards
    b. Performance-based design recommendations
    c. Performance-based design standards
    d. Prescriptive recommendations

47. In the Eurocodes thermal actions applied to energy geostructures will be classified as
    a. Permanent actions
    b. Variable actions
    c. The choice is left to the designer
    d. A combination of the three

48. Which are the main considerations that can be concluded for the analysis and design of energy geostructures at ULS and SLS

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**

49. The driving cause of heat transfer by conduction is generally considered to be:
    a. The motion of a fluid
    b. An invisible motion of the particles that constitute a medium
    c. Waves of the electromagnetic field propagating at the speed of light

50. Write the mathematical expression of Fourier's law and define the involved terms.

$$\dot{q}_{cond,i} = \frac{Q}{At} = \frac{\dot{Q}}{A} = -\lambda\frac{\partial T}{\partial n_i} = -\lambda\nabla T = -\lambda\left(\frac{\partial T}{\partial x}\hat{e}_x + \frac{\partial T}{\partial y}\hat{e}_y + \frac{\partial T}{\partial z}\hat{e}_z\right)$$

where the $\dot{q}_{cond,i}$ is the heat flux density (i.e., the rate of heat energy, Q, transferred through a given surface, A, per unit time, t) generated by conduction, λ is the thermal conductivity of the medium (the parameter, i.e., a positive scalar quantity, that governs heat conduction), T is the temperature, n_i is a considered direction, ∇ is the vector differential operator (gradient), and $\hat{e}_x$, $\hat{e}_y$ and $\hat{e}_z$ are the standard unit vectors in Cartesian (also termed rectangular) coordinates.

51. Heat transfer by convection can be free (i.e., natural) or forced. Provide a description of these two processes, highlighting the crucial differences between them.

Free or natural convection: when the force that causes the motion of the fluid is due entirely to density variations caused by a non-uniform temperature distribution.
Forced convection: the force that causes the motion of the fluid is due to any other cause.

52. Which is the fundamental parameter that allows understanding if convection plays a major role in the heat transfer in soils? To which law is this parameter related? Write the considered law. Define the different terms involved.

The parameter governing this aspect is the convection heat transfer coefficient, h_c, which depend on the nature of the fluid in motion and an assortment of fluid thermodynamic and transport (mass) properties. In the analaysis of internal and external flows related to airflows is often expressed as $h_c = h_{c,n} + h_{c,f}$. This parameter is related to the Newton's law of cooling

$$\dot{q}_{conv,i} = h_c(T_s - T_\infty)$$

where $\dot{q}_{conv,i}$ is the energy density by convection, h_c is the convection heat transfer coefficient, T_s is the surface temperature and T_∞ is the fluid temperature

53. Is it reasonable to foresee thermal energy storage through energy geostructures for a site that is characterised by significant groundwater flow? Why?

No it is not. The stored heat would be transferred away because of the groundwater flow.

54. Consider an energy pile located below a very large raft of a building and operating as geothermal heat exchanger. Assume that a very thick thermal insulation layer is placed at the uppermost surface of the slab, so that no influence of the ambient conditions is experienced in the subsurface. Consider that the soil is saturated and that no groundwater flow occurs. Which is/are the main mode/s of heat transfer occurring in the soil?

    Conduction.

55. Write the simplified Fourier heat conduction equation and define the parameters involved in this expression. Neglect any conversion of mechanical energy into heat. Consider a body characterised by arbitrary thermal conditions on its surfaces, internal volumetric heat generation as well as constant thermal conductivity.

$$\boldsymbol{\lambda \nabla^2 T + \dot{q}_v = \rho c_p \frac{\partial T}{\partial t}}$$

where λ is the thermal conductivity of the medium, ∇^2 is the Laplace operator, T is the temperature, $\dot{q}_v$ is a volumetric heat source, ρ is the bulk density of the medium, c_p is the specific heat and t is the time.

56. What is the unit measure of thermal conductivity?
    a. W/°C
    b. °C/W
    c. °C/m
    d. W/(m °C)

57. Which is the mathematical expression of the thermal diffusivity? Define all of the parameters that are included in this expression.

$$\boldsymbol{\alpha_d = \frac{\lambda}{\rho c_p}}$$

where λ is the thermal conductivity of the medium, ρ is the bulk density of the medium, and c_p is its specific heat.

58. Calculate the effective thermal conductivity, λ, of a dry sand at the temperature level of 15 °C characterised by a porosity $n = 0.42$ and a value of thermal conductivity of solid particles $\lambda_s = 0.41$ W/(m °C). Repeat the calculation for the same sand assuming it is fully saturated with water. Comment on the results and on the impact of the different values of λ on the heat exchange characterising an adjacent energy pile.

Thermal conductivity of air at ambient temperature is $\boldsymbol{\lambda_a = 0.025}$ W/(m °C). Therefore, the effective thermal conductivity calculated as weighted arithmetic mean of the thermal conductivities of its components reads

$$\boldsymbol{\lambda = n\lambda_a + (1-n)\lambda_s = 0.25 \text{ W/(m °C)}}$$

The thermal conductivity of water at ambient temperature is $\boldsymbol{\lambda_w = 0.58}$ W/(m °C). Hence, for the case in which the sand is saturated with water the effective thermal conductivity reads

$$\boldsymbol{\lambda_{sat} = n\lambda_w + (1-n)\lambda_s = 0.48 \text{ W/(m °C)}}$$

The above explains why a thermal conductor present in the soil pores such as water strongly increases the heat exchange between, e.g., an energy pile and the surrounding soil, contrary to what happens with a thermal insulator like air.

59. Soils of large thermal diffusivity respond:
   - **a. Quickly to changes in their thermal environment**
   - b. Slowly to changes in their thermal environment
   - c. Irrespectively of the changes of their thermal environment
   - d. Depending on the thermal conductivity

60. List at least three of the five boundary conditions that are used in the mathematical theory of heat transfer as idealisations for any portion of the bounding surface of a considered medium.

Prescribed surface temperature (Dirichlet's boundary condition or boundary condition of the first kind);
Prescribed heat input (Neumann's boundary condition or boundary condition of the second kind);
Convection boundary condition (Cauchy's or mixed Neumann's boundary condition or boundary condition of the third kind)
Radiation boundary condition (Cauchy's or mixed Neumann's boundary condition or boundary condition of the third kind);
Interface boundary condition.

61. Under steady conditions, the heat transfer occurring within energy geostructures can be modelled with:
    a. A time-dependent approach
    b. A time-independent approach
    c. None of the above

62. The concept of thermal resistance can be used:
    a. To characterise heat transfer as a purely resistance process
    b. To characterise electrical current flow as a purely resistance process
    c. To characterise groundwater flow as a purely resistance process

63. Which are the three fundamental heat transfer processes that are considered in the definition of the time-independent part of the thermal resistance?

    Convective heat transfer between the circulating heat carrier fluid and the inner surface of the pipes;
    Conductive heat transfer through the wall of the pipe;
    Conductive heat transfer through the grouting material.

64. Explain the concept of thermal resistance in reference of the time-dependent modelling of heat transfer.

The thermal resistance in reference of the time-dependent modelling of heat transfer considers the transient phenomena occurring in a larger domain surrounding a single body or multiple bodies for t>t* (typically, the ground surrounding the geothermal heat exchanger/s). The considered thermal resistance is referred as the total thermal resistance, R_T(t), and is decomposed into a time-independent part and a time-dependent part as

$$\boldsymbol{R_T(t) = R_{ghe} + G_f(x_i, t)} \quad [°C/W]$$

Where R_{ghe} is the time-independent part of the total thermal resistance, typically coinciding with the thermal resistance of the geothermal heat exchanger, and $G_f(x_i, t)$ is the time-dependent part of the total thermal resistance, often called G-function.

65. Provide the mathematical formulation of the infinite cylindrical surface source model of a geothermal heat exchanger with a constant heat flux around its surface at $r=R$ equal to $\dot{q}_l$, initially at a temperature $T=T_0$

The model is expressed mathematically as

$$\begin{cases} \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha_d}\frac{\partial T}{\partial t} \\ r = R - 2\pi R \lambda \frac{\partial T}{\partial t} = \dot{q}_l \\ r \to \infty \qquad T = T_0 \\ t = 0 \qquad T = T_0 \end{cases}$$

Where *r* is the radial distance from the axis of the cylinder, *T* is the temperature of the body, α_d is the thermal diffusivity, *R* is the radius of the cylindrical surface, λ is the thermal conductivity, $\dot{q}_l$ is the heat flux per unit length, T_0 is the initial temperature and *t* is the time.

66. List four mathematical models that can be used to describe the time-dependent heat transfer around energy geostructures. Which heat transfer mode is accounted for in these models?

Infinite cylindrical-surface source model;
Infinite line source model;
Continuous spherical source model;
Source model for a semi-infinite medium.

Conduction.

67. An advantage of a laboratory test is to be performed
    a. In the natural state of soil
    b. In a controlled environment
    c. None of the above

68. The estimation of the thermal potential allows to have a good estimate of the actual performance of energy geostructures
    a. True
    b. False

69. The thermal properties of interest are
    a. The initial temperature
    b. The thermal conductivity
    c. The volumetric heat capacity

70. The needle probe method allows to consider
    a. Steady state and transient condition

b. Steady state condition
c. Transient condition

71. The potential anysotropy condition in site of the soil can be better taken into account with
    a. The needle probe method
    b. The divided bar method

72. The TRT allow to define the following parameters
    a. The time-independent resistance
    b. The effective thermal conductivity
    c. The time-dependent resistance
    d. Undisturbed ground temperature

73. It is suggested to perform TRT test
    a. For borehole
    b. For energy pile
    c. For borehole and energy pile
    d. For energy pile and walls

74. Thermal loading is usually associated with
    a. Undrained conditions
    b. Drained conditions
    c. Both of them

75. The volumetric soil behavior is usually assessed experimentally through
    a. Oedometric test
    b. Triaxial test
    c. Direct shear test
    d. Oedometric test and triaxial test

76. Pre-consolidation pressure is temperature dependent
    a. True
    b. Faulse

77. For the temperature levels characterising energy geostructure applications a thermo-plastic behaviour upon a heating-cooling cycle is typical of soil
    a. In NC conditions
    b. In highly OC conditions
    c. In slightly OC conditions

78. In the thermo-elasticity framework thermal load can induce
    a. Change in shape
    b. Rigid body motion
    c. Change in volume
    d. A combination of the three

79. Describe the essential features of the behaviour of fine-grained soils to one heating-cooling cycle depending on the consolidation state.

    Under normally consolidated conditions (NC), fine grained-soils contract when heated and a significant part of this deformation is not recovered upon cooling. Under highly over consolidated conditions (OC), fine-grained soils expand when heated and this deformation is entirely recovered upon cooling. Under slightly OC conditions, fine-grained soils show an initial expansion and subsequent contraction when heated, followed by a tendency towards contraction upon cooling.

80. The angle of shear strength of soils under constant volume conditions markedly varies with temperature:
    a. True
    b. False