Thermo-mechanical analysis of single energy piles

Introduction

Consider an energy pile of 20 m in length and 0.8 m in diameter that is a part of the square group of energy piles reported in Figure 1. Assume that the energy pile is socketed in a saturated sand deposit and that a 12×12 m rigid slab (resting on the ground) made of reinforced concrete connects all the energy piles. The sand and the pile proprieties are reported in Table 1 and Table 2, respectively.

Evaluate the bearing capacity of the energy pile (i) assuming it as a non-displacement pile, (ii) by using a long-term analysis approach (i.e., in terms of effective stresses), and (iii) considering the Hansen's method (Hansen 1970) for the evaluation of the base contribution of capacity.

By using the software Thermo-Pile (Knellwolf et al. 2011) and referring to the relations proposed by Frank et al. (1991) for piles in coarse-grained soils, evaluate the vertical stresses and displacements developed in the considered energy pile, assumed to be a single isolated element, in five different cases:

- CASE 1: pile free at the head subjected to a vertical load of $P = 500$ kN and to a temperature change of $\Delta T = 0$ °C.
- CASE 2: pile free at the head subjected to a vertical load of $P = 0$ kN and to a temperature change of $\Delta T = 10$°C.
- CASE (1+2): pile assumed to be characterised by the effects induced by the loads considered in CASE 1 and CASE 2 through an elastic superposition principle.
- CASE 3: pile free at the head subjected to a vertical load of $P = 500$ kN and to a temperature change of $\Delta T = 10$ °C.
- CASE 4: pile restrained at the head by the presence of the slab and subjected to a vertical load of $P = 500$ kN and to a temperature change of $\Delta T = 10$ °C. Assume that the slab stiffness can be estimated through the following equation, with reference to a rigid rectangular plate resting vertically loaded on an isotropic elastic half-space (Gorbunov-Posadov and Serebrjanyi 1961):

$$K_{slab} = \frac{E_{soil}\sqrt{B_{slab}L_{slab}}}{(1 - {v_{soil}}^2)\rho_0}$$

where E_{soil} is the Young's modulus of the soil, B_{slab} and L_{slab} are the dimensions of the slab, v_{soil} is the Poisson's ratio of the soil, and ρ_0 is a displacement coefficient. Consider that the displacement coefficient can be evaluated as a function of the ratio $\chi = L_{slab}/B_{slab}$ using Figure 2.

For each case, plot the evolutions along the length of the energy pile (discretised in 200 elements in Thermo-Pile) of the vertical stress, shear stress and vertical displacement induced by the applied mechanical and/or thermal loads. Compare and discuss the differences between the obtained results through a short resume for each case, with a particular focus on the reason why CASE (1+2) and CASE 3 differ. Compare as well in each case the obtained results with the thermo-mechanical schemes discussed during the course. To which extent are these charts representative of the actual behaviour of energy piles?

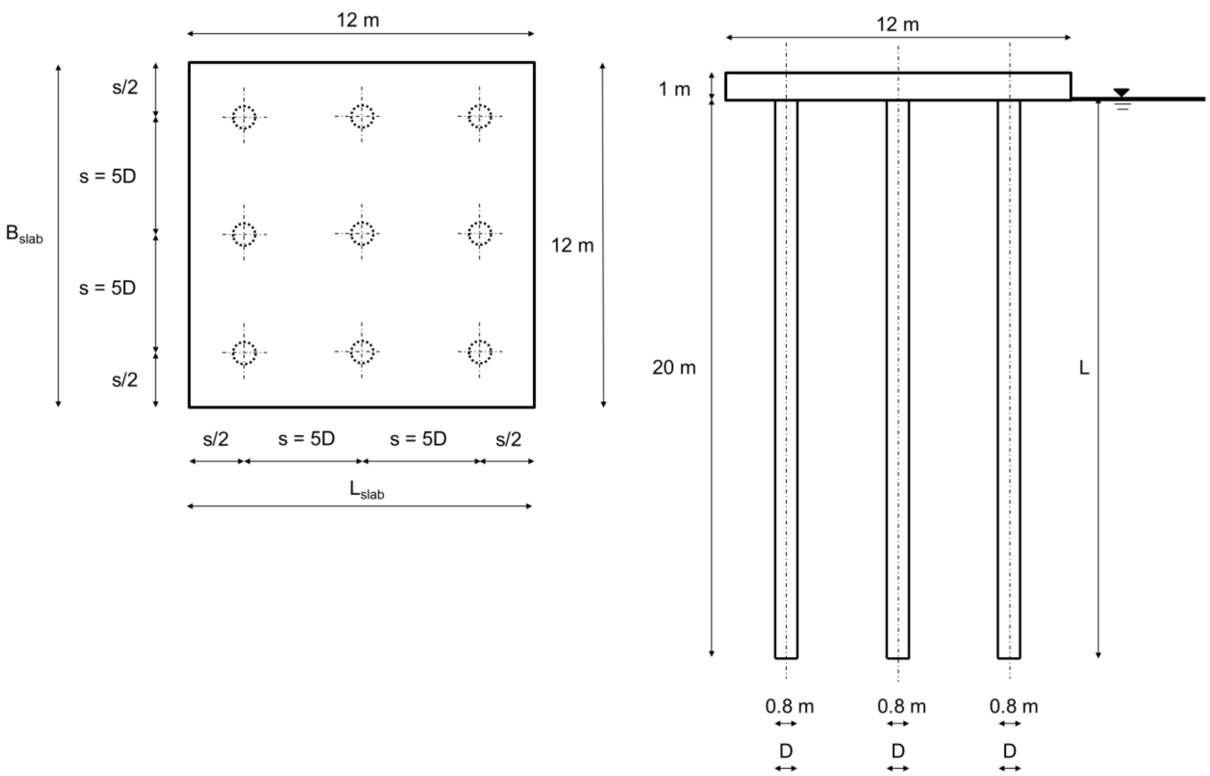

Figure 1. The problem.

Table 1. Sand properties.

	γ_{soil}	c'	φ'_{cv}	φ'	E_{soil}	ν_{soil}	α_r
	[kN/m^3]	[kPa]	[°]	[°]	[MPa]	[-]	[-]
Sand	19	20	31	38	78	0.3	0.33

Table 2. Pile properties.

	$\gamma_{concrete}$	E_{EP}	v_{EP}	α_{EP}
	[kN/m^3]	[MPa]	[-]	[με/°C]
Pile	25	30000	0.25	10

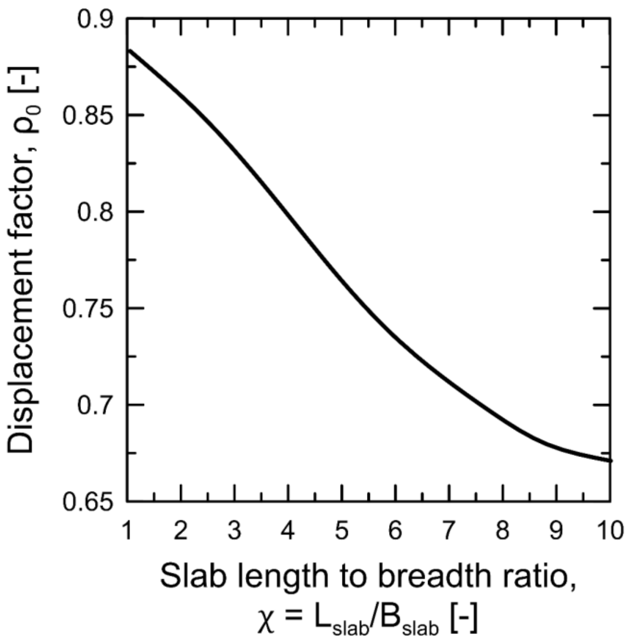

Figure 2. Displacement coefficient of a rigid rectangular plate resting on an isotropic elastic half-space (Gorbunov-Posadov and Serebrjanyi 1961).

Solution

For a non-displacement pile, the coefficient $\overline{K}$ can be taken according to Kulhawy et al. (1983) as:

$$\overline{K} = 0.7K_0 = 0.7\,(1 - \sin\varphi'_{cv}) = 0.7 \cdot (1 - \sin 31) = 0.34$$

while the pile-soil interface angle of shear strength, δ, can be considered to be $\delta = \varphi'_{cv}$ so that:

$$\tan\delta = \tan\varphi'_{cv} = 0.6$$

Therefore, the shaft capacity reads:

$$Q_s = q_s A_s = \overline{K\sigma'_v}\tan\delta\, A_s = 0.34 \cdot (19 - 10) \cdot \frac{20}{2} \cdot 0.6 \cdot \pi \cdot 0.8 \cdot 20 = 923 \text{ kN}$$

The base capacity, neglecting the terms involving the bearing capacity factors N_c and N_γ and assuming a shape factor $s_q = 1$, can be evaluated according to the method proposed by Hansen (1970) as:

$$Q_b = q_b A_b = \sigma'_{vb} N_q d_q A_b = \gamma'_{sand} L K_p e^{\pi \tan \varphi'_{cv}} \left(1 + 2 \tan \varphi'_{cv} \left(1 - \sin \varphi'_{cv}\right)^2 k\right) \pi \left(\frac{D}{2}\right)^2$$
$$= \gamma'_{sand} L \frac{\left(1 + \sin \varphi'_{cv}\right)}{\left(1 - \sin \varphi'_{cv}\right)} e^{\pi \tan \varphi'_{cv}} \left(1 + 2 \tan \varphi'_{cv} \left(1 - \sin \varphi'_{cv}\right)^2 k\right) \pi \left(\frac{D}{2}\right)^2$$

Based on the available data:

$$K_p = \frac{\left(1 + \sin \varphi'_{cv}\right)}{\left(1 - \sin \varphi'_{cv}\right)} = \frac{(1 + \sin 31)}{(1 - \sin 31)} = 3.12$$

$$N_q = K_p e^{\pi \tan \varphi'_{cv}} = 3.12 \cdot e^{\pi \cdot \tan 31} = 20.6$$

$$k = \tan^{-1}\left(\frac{L}{D}\right) = 1.53$$

$$d_q = 1 + 2 \tan \varphi'_{cv} \left(1 - \sin \varphi'_{cv}\right)^2 k = 1 + 2 \cdot \tan 31 \cdot (1 - \sin 31)^2 \cdot 1.53 = 1.43$$

Therefore, the base capacity is:

$$Q_b = q_b A_b = \sigma'_{vb} N_q d_q A_b = 180 \cdot 20.6 \cdot 1.43 \cdot \pi \cdot \left(\frac{0.8}{2}\right)^2 = 2665 \text{ kN}$$

For the analyses to be run with the software Thermo-Pile, a number of parameters must be determined. These are the Menard pressuremeter modulus, E_M, and the stiffness of the slab, K_{slab}.

The Menard pressuremeter modulus of the sand that can be estimated as follows:

$$E_M = E_{oed} \alpha_r$$

where E_{oed} is the oedometric modulus.

The oedometric modulus can be calculated as:

$$E_{oed} = \frac{E_{soil}(1 - v_{soil})}{(1 + v_{soil})(1 - 2v_{soil})} = \frac{78000 \cdot (1 - 0.3)}{(1 + 0.3) \cdot (1 - 2 \cdot 0.3)} = 105000 \text{ kPa}$$

Therefore, the Menard pressuremeter modulus reads:

$E_M = E_{oed}\alpha_r = 105000 \cdot 0.33 = 34650 \text{ kPa}$

To evaluate the slab stiffness, the following equation can be used:

$$K_{slab} = \frac{E_S\sqrt{B_{slab}L_{slab}}}{(1-v_{soil}{}^2)\rho_0} = \frac{78000\cdot\sqrt{12\cdot12}}{(1-0.3^2)\cdot0.88} = 1168831 \text{ kN/m}$$

Hence, the stiffness of the slab per unit cross-sectional area of energy pile is:

$$K^*_{slab} = \frac{K_{slab}}{\text{n}_{EP}A_{EP}} = \frac{1168831}{9\cdot0.503} = 258.368 \text{ kPa/m}$$

The results obtained with the Thermo-Pile software are reported below.

CASE 1

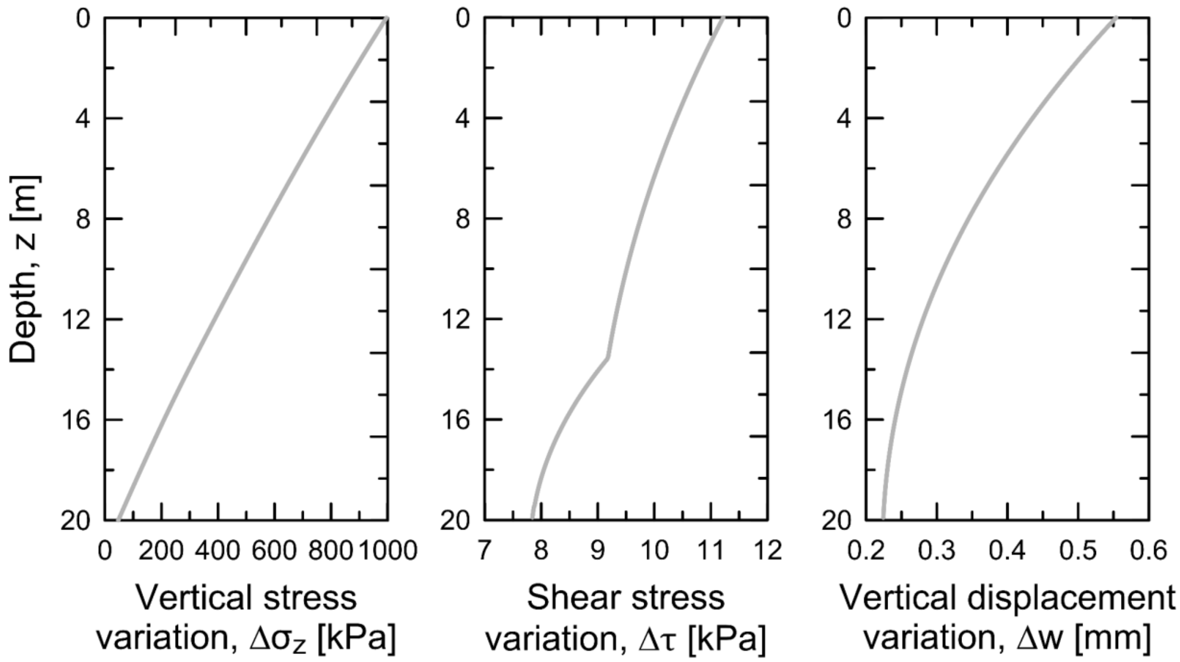

Figure 3. Results for CASE 1.

CASE 2

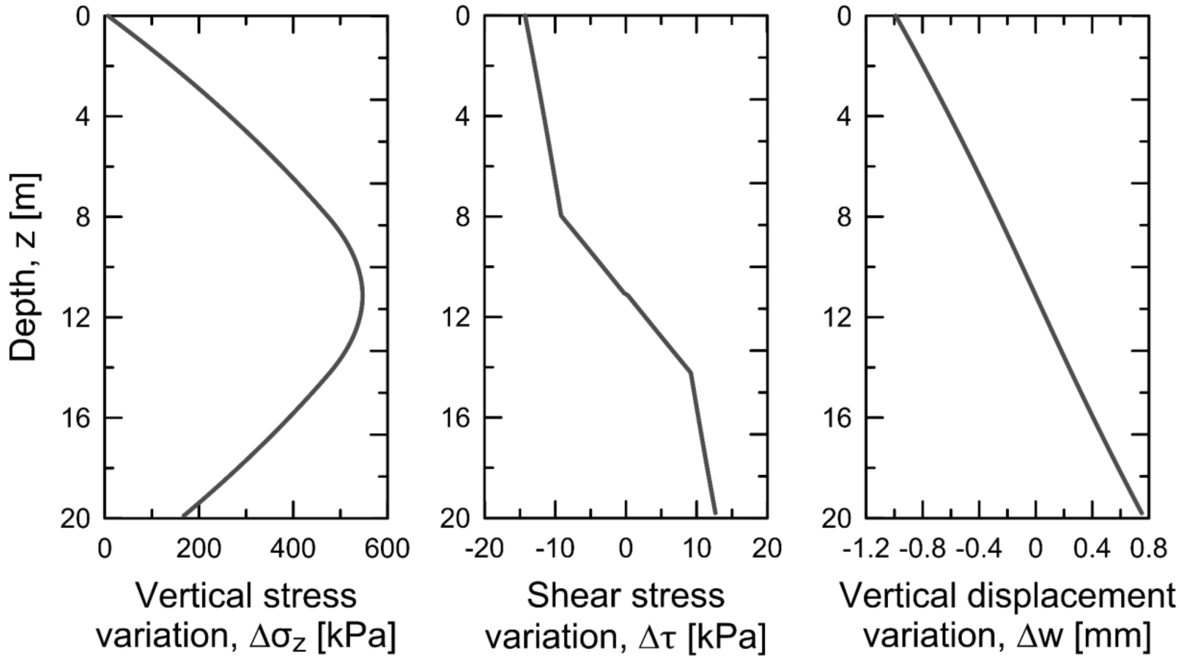

Figure 4. Results for CASE 2.

CASE 1+2

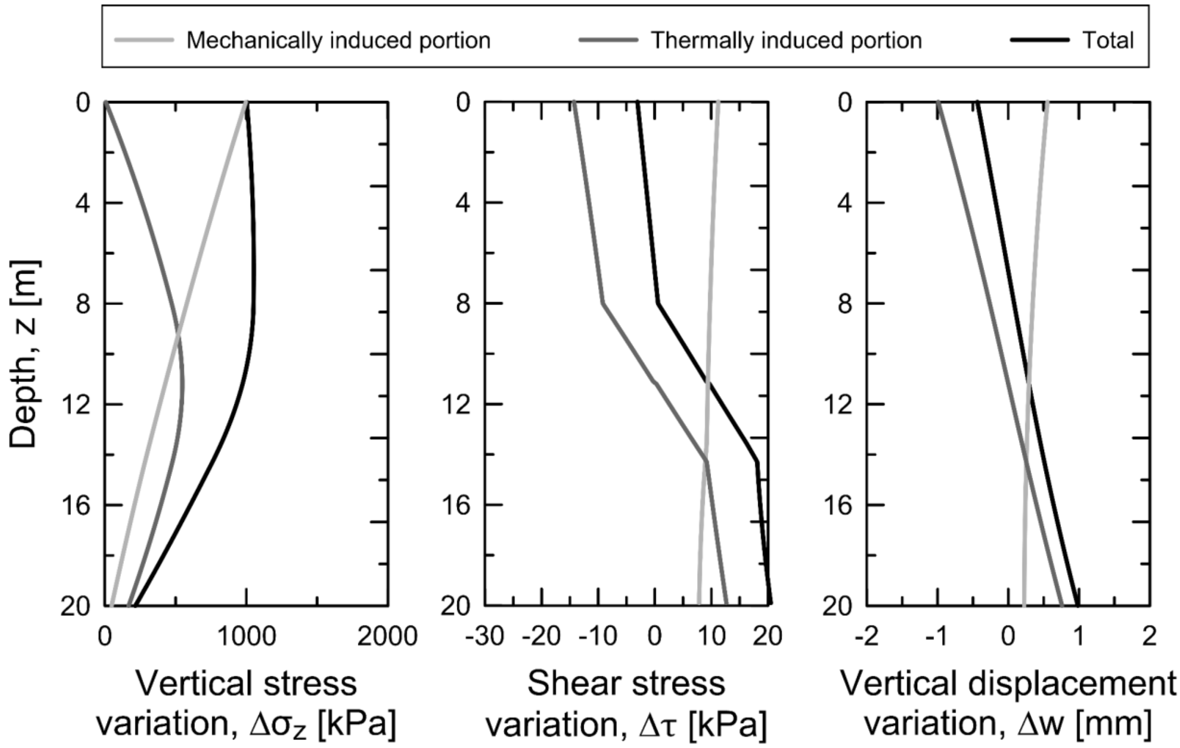

Figure 5. Results for CASE 1+2.

CASE 3

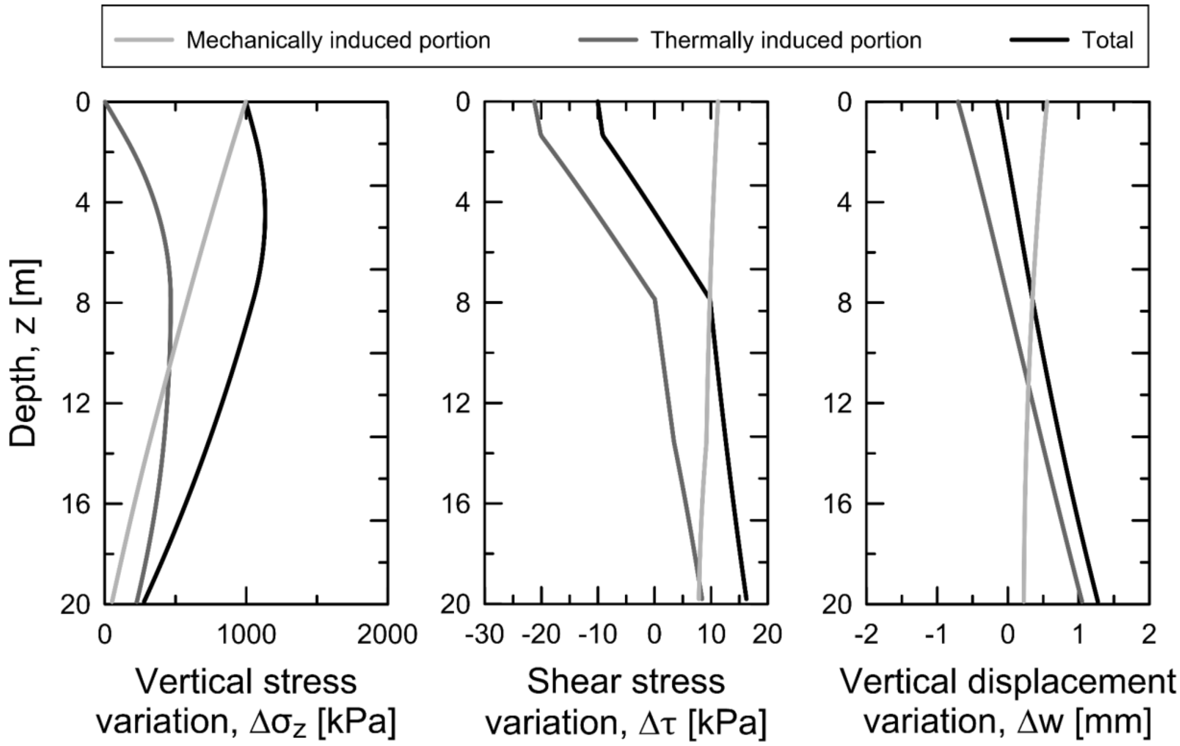

Figure 6. Results for CASE 3.

CASE 4

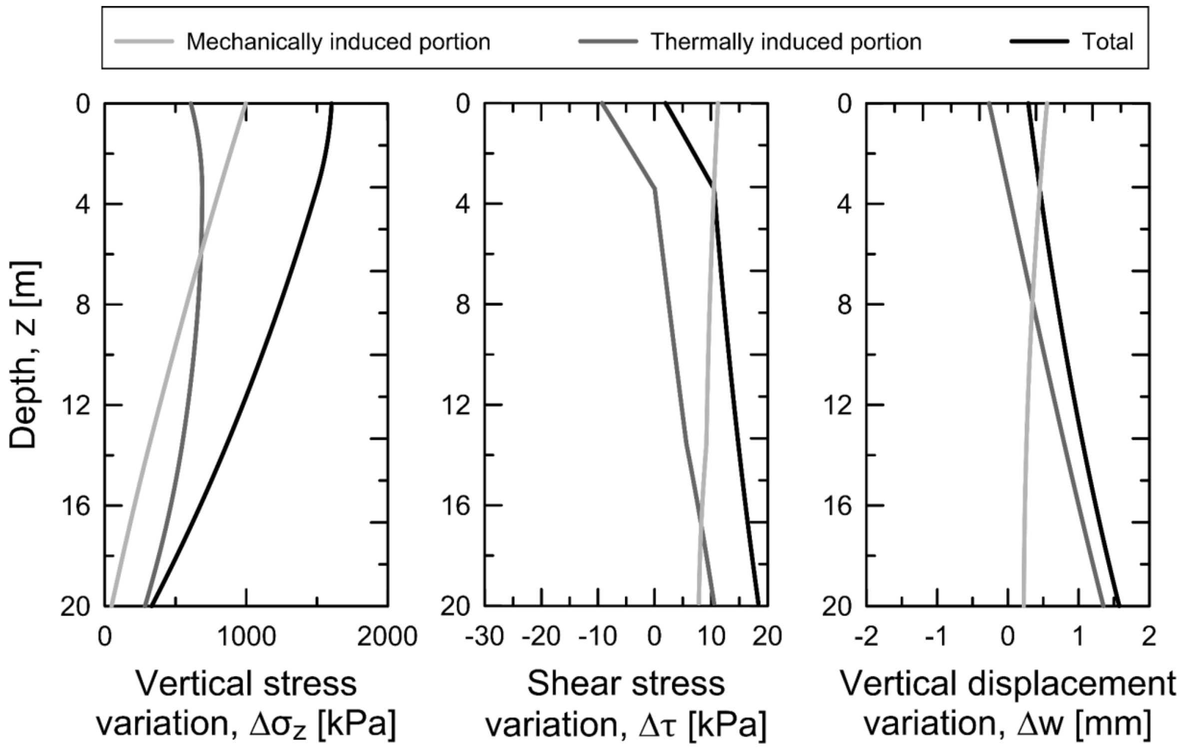

Figure 7. Results for CASE 4.

References

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