Thermo-mechanical radial expansion of heat exchanger piles and possible effects on contact pressures at pile-soil interface

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This letter shows that the increase of heat exchanger pile capacity in response to heating, observed in several small-scale laboratory studies cannot be directly attributed to the increase of contact pressure at the soil/pile interface. The main thermo-hydro-mechanical processes that influence the capacity and behavior of heat exchanger piles include thermal hardening of the soil, thermally induced water flow, excess pore pressure development and volume changes upon thermal consolidation. Due to the lack of understanding of the behaviour around the soil-pile interface, thermo-mechanical interactions between the heat exchanger pile and the ground are not taken into account appropriately in energy foundation design. However, in situ and reduced-scale experiments provide evidence about temperature-induced changes in pile capacity, presumably as a result of the altered stress state around the test pile. A Finite Element analysis was conducted to quantitatively assess the radial stresses and strains undergone by a heated pile embedded in deformable soil. The study indicates that radial contact pressures typically increase less than 15 kPa, which cannot fully explain the increase of shaft resistance observed in heating tests. Further analyses are underway to characterize the mechanisms that govern pile load-displacement behavior and limit state.

Pile capacity; finite-element modelling; friction; piles; temperature effects; theoretical analysis; cavity expansion theory

List of Notation

E_p (kPa)	Young's modulus of the pile
E or E_s (kPa)	undrained Young's modulus of the soil
k_p (kN/m)	equivalent rigidity of the spring representing the pile
k_s (kN/m)	equivalent rigidity of the spring representing the soil
R (m)	radius of the pile
s_u (kPa)	undrained shear strength of the soil
T (°C)	temperature
α (1/°C)	thermal expansion coefficient
ε_r (-)	radial strain
λ_s (m)	zone of influence within the soil
σ_r (kPa)	radial stress

INTRODUCTION

The operation of heat exchanger piles creates differential temperatures between the pile and the soil around the pile. The thermo-elastic radial expansion of the heat exchanger pile and consequent increased contact pressures at the pile-soil interface is thought of as one of the possible mechanisms underlying changes in shaft resistance measured in several thermo-mechanical pile load tests. The main purpose of this letter is to investigate if increased pile capacity at higher temperatures can be attributed to thermal expansion. A summary of thermo-hydro-mechanical soil-structure interaction processes is provided in the context of temperature effects on heat exchanger pile response. In addition, a review of experimental studies on the load-displacement behavior of heat exchanger piles at different temperatures is reported (Second Section). Finite Element analyses are presented (Third Section) to study the radial deformations and the magnitude of the stresses that develop around a pile subjected to a temperature increase. The results of the analyses provide insight on the magnitude of temperature-induced contact stresses on heat exchanger piles and the expected effect on shaft friction for a range of soil strength and stiffness values.

THERMO-HYDRO-MECHANICAL SOIL-STRUCTURE INTERACTION IN HEAT EXCHANGER PILES

Performance of heat exchanger piles can be affected by the temperature changes induced by heat exchange operations. Anisotropic thermal fields within the pile and the surrounding soil produce relative deformations between the soil and the pile, depending on the fixity conditions of the pile (Bourne-Webb et al. 2009). These deformations can induce slip at the pile-soil interface, which can modify the shear stress transfer between the pile and the soil. This can change the internal stresses along the pile in addition to those caused by the structural load. Seasonal elongation and shortening of the heat exchanger pile results in repeated cyclic shear straining, which can potentially affect the properties of the soil-pile interface, hinder the pile's frictional resistance, reduce its axial load capacity, and may cause unanticipated settlements or eventually result in failure. These types mechanisms were already noted in studies focusing on offshore pile behaviour under cyclic loads (Poulos 1989, Jardine and Standing 2000).

Furthermore, soil behaviour is affected by thermal history related to the heating/cooling cycles imposed by the heat exchanger pile. For instance, temperature changes can result in excess pore pressures (Campanella and Mitchell 1968, Uchaipichat and Khalili 2009), volume changes (Baldi et al. 1988, Cekerevac 2003, Abuel-Naga et al. 2005,) and can also affect the yield pressure of the soil (Eriksson 1989, Moritz 1995, Leroueil and Marques 1996). These processes are likely to result in deformations and stresses that are not typically considered in foundation design. The long-term effects of repeated thermal consolidation cycles are still not well understood. There is a potential risk that fatigue-like processes can considerably degrade the strength and stiffness of clayey soils along the shaft interface. Furthermore, moisture migration away from the heat exchanger pile can cause local desaturation of the soil, and reduce thermal conductivity - similar to the thermal instability observed in buried cables (Brandon et al. 1989). Such phenomena would significantly hinder the thermal performance of heat exchanger piles.

A variety of experimental and analytical studies has been performed to investigate the thermo-mechanical behaviour of heat exchanger piles, including temperature effects on soil behaviour and shear stress mobilization/relaxation at the pile-soil interface due to thermo-elastic pile deformations (Brandl 2006, Laloui et al. 2006, Bourne-Webb et al. 2009, Knellwolf et al. 2011). Researchers at the University of Colorado at Boulder have performed load tests on semi-floating heat exchanger piles in a centrifuge using partially saturated Bonny silt compacted around the pile. The test pile was heated to different temperatures before applying the structural load (Rosenberg 2010). This study demonstrates the effect of temperature on the load-displacement behaviour of heat exchanger piles. Fig. 1 and Table 1 show that the pile has an increased head stiffness and capacity at higher temperatures. At first glance, this experimental study presents evidence about the temperature-induced changes in pile capacity, presumably as a result of the altered stress state around the test pile (McCartney and Rosenberg 2011).

A summary of other experimental studies investigating temperature effects on the load-displacement behavior of heat exchanger piles is provided in Table 2. These studies utilized small-scale models tested under 1-g or at increased g-levels in the centrifuge to represent field-scale stresses. Wang et al. (2011, 2012) tested small-scale piles at different temperatures using loosely compacted dry and partially saturated N50 fine sand. They noted no change in shaft resistance with dry sand and a decrease in shaft resistance with the partially saturated sand at elevated temperatures. They also measured decreased shaft resistance at higher temperatures with piles tested in partially saturated 300WQ silica flour. Similarly, Kramer and Basu (2014) performed similar small-scale tests under 1-g using dry F50 Ottawa sand and observed a slight increase (~5%) in pile capacity at increased temperatures. Goode et al. (2014) performed experiments in the centrifuge with dry Nevada sand and measured no apparent change in pile response at different temperatures. As observed, the load-displacement measurements of the tested piles at increased temperatures in these studies show different trends. These tests represent different testing conditions, materials, and model preparation techniques, which are presumably reflected in the observed behavior through different mechanisms.

It is quite conceivable that the thermo-hydro-mechanical processes described above can play a role in affecting heat exchanger pile capacity at elevated temperatures. For instance, pore pressure development and thermal consolidation in soft saturated clays can alter the stress state and result in deformations around a heat exchanger pile. Similarly, thermally induced moisture migration followed by increased effective stress in unsaturated soils may play a role on pile behavior. Stewart and McCartney (2013) performed tests on end-bearing heat exchanger piles in the centrifuge using partially saturated compacted Bonny silt. They measured a reduction in moisture content near the heated pile and attribute the increased pile resistance under similar conditions to increase in effective stresses and higher shaft resistance. It is also possible that lateral pressures induced by compaction around the test pile may have affected the overall behavior of the piles tested in this study as well as the tests reported in McCartney and Rosenberg (2011). However it is not clear as to how these stresses played a role in different shaft resistances at increased temperatures.

The goal of this letter is to investigate the magnitude of changes in contact pressure between the soil and the pile, as a result of the temperature-induced radial deformation of the heat exchanger pile. This phenomenon is postulated as one of the possible mechanisms of increased shaft resistance at higher temperatures (McCartney and Rosenberg 2011, Stewart and McCartney 2013, Goode et al. 2014). Temperature-induced expansion of the pile will result in increased lateral stresses, thereby affecting frictional resistance along the pile shaft. The mechanical behaviour of the pile is expected to lie between free expansion under temperature increase (in the absence of soil, Fig. 2.a) and constrained heating building up internal thermal stress (in the presence of a fixed support, Fig. 2.b). These represent lower and upper bounds for the expected radial stress development in actual field conditions: deformable soil partially restrains the free expansion of the pile, without fully preventing it. In the absence of development of soil plasticity, the problem of temperature-induced confining pressures may be viewed as a hyperstatic thermo-elasticity problem illustrated by the two springs in Fig. 2.c.

2D NUMERICAL ANALYSIS OF SOIL CONTACT PRESSURE INDUCED BY PILE HEATING

A Finite Element model has been developed with COMSOL Multiphysics software platform to study the influence of radial thermal expansion on the increase of contact pressure applied by the soil on the pile (COMSOL 2013). The mesh and its dimensions are shown in Fig. 3. The pile is modeled as a thermo-elastic medium, while the soil is assumed to follow a Tresca linearly elastic – perfectly plastic behaviour. The soil and pile elements share the same nodes at the pile-soil interface. The initial temperature of the soil and the pile is 15°C and the external boundary of the model is fixed. Material parameters used in the analyses are listed in Table 3. Undrained soil stiffness is assumed to be proportional to undrained shear strength as $E=1000\times s_u$: this is a median value for the stiffness/strength ratio (Jardine et al. 1984). Undrained conditions were considered in the total stress analyses while the pore water pressure development and water flow was not considered.

Stationary analyses were performed to establish the magnitude of soil resistance in response to thermal pile expansion. In these analyses, the soil temperature is maintained at its initial value (15°C), and the temperature of the pile is raised to 25°C. Even though these analyses do not represent field conditions during heat exchange operations where the soil temperature also increases, they provide baseline values for increased stresses that develop as a result of thermal pile expansion only. Young's modulus (E) of the medium around the pile is systematically varied between 10^2 kPa and 10^{12} kPa, to represent different levels of lateral restraint at the pile face. In this case, stiffness of the hypothetical medium around the pile greatly exceeds the range of typical values for soils, in order to represent full range of cases from free pile face to full fixity. Fig. 4 shows that for $E<10^6$ kPa, the total radial strain of the pile is equal to the thermal strain, which means that the mechanical strain induced by the reaction of the soil is negligible: the pile face deforms freely as a result of thermal expansion. As a matter of fact, the deformation of the soil is equal and opposite in sign to that of the pile $\varepsilon_r = 10^{-4}$. For $E>10^9$ kPa, the presence of the soil prevents the pile from expanding: radial strains in the soil and in the pile are close to zero. For 10^6 kPa < E < 10^9 kPa, the soil acts as a spring, and applies a restraint to the pile in reaction to its thermal expansion. For realistic values of soil modulus (between 5×10^3 kPa and 10^5 kPa), a pile subjected to heating embedded in isothermal soil is expected to expand freely, as evidenced by total pile strains being near-equal to thermal strains and thus mechanical pile strains being very close to zero. This shows that, the soil provides almost no constraint to thermal pile expansion: the pile's response is close to that of the free pile shown in Fig. 2.a. A cavity expansion problem was also simulated for verification purposes, by applying the radial strains of the pile face on the cavity wall. The results, displayed in Fig. 5, show that for $E>10^9$ kPa, thermo-mechanical stresses around 3.5 MPa build up at the pile-soil interface, equivalent to those that would develop upon a pressurization of a fixed cylindrical cavity.

Transient analyses were performed to check whether the thermal expansion of the soil has a considerable influence on the increase of contact stress at the pile face. Compared to the stationary analyses, transient analyses provide a more realistic representation of field conditions where the heated soil also expands during heat exchange operations and induces additional radial stresses on the pile: soil mechanical behaviour is coupled with thermo-elasticity and heat transfer is governed by the diffusion equation. Undrained strength values of s_u = 25, 50 and 100 kPa were selected to represent soft, medium and stiff clay while the undrained soil stiffness is assumed to be proportional to undrained shear strength as $E=1000\times s_u$. The pile was subjected to a linear temperature increase during 12 hours, from an initial temperature of 15°C up to 25°C (typical of a heat exchanger pile operating in building cooling mode). This temperature was maintained for 12 hours. Computed temperature variations within the soil are shown in Fig. 6.

The 2D cross-sectional analyses considered both plane strain and plane stress conditions. In the plane stress analysis, the cross-section is free to deform in the out-of-plane direction and in the plane-strain analysis out-of-plane deformation is fully fixed. Total strains in the pile and the soil in response to heating are shown in Fig. 7 for plane stress and plane strain conditions. Stationary and transient analyses results are provided together for comparison. Strain plots are the same for all the soils analysed, which confirms the thermo-elastic response of the pile and the soil. The radial strain of the pile is equal to the strain of a pile in free thermal expansion, which confirms the negligible resistance from the soil similar to the results presented in Fig. 4. In plane stress (Fig. 7.a), the radial deformation of the pile is purely thermal. In plane strain (Fig. 7.b), the radial deformation of the pile occurs as a result of thermal expansion and Poisson's effects due to the constraint along the out-of-plane direction.

In the stationary analyses, radial strains in the soil, which occur as a result pile expansion, are purely compressional. These strains are negligible beyond 1.2 m away from the pile face. In the transient case, the radial strains in the soil occur as a result of the thermal expansion of both the pile and the soil. The soil surrounding the pile exhibits extensional radial strains within a distance equal to no more than half the pile diameter. Presumably, the compression induced by the expanding pile is overcome by the thermal expansion of the soil, which has five times the thermal expansion coefficient of the pile. Thermal expansion of the heated soil zone is also imposing compressional radial strains from about a half pile diameter to about 2.7 m away from the pile face, a distance about four and a half times the pile diameter. The magnitudes of these compressional strains are larger and expand beyond those induced only by thermal expansion of the pile as seen from stationary analysis.

Computed radial stresses within the pile and the soil are shown in Fig. 8 for all the considered cases. Radial stresses in the soil are compressive both for stationary and transient cases for soils with different strength values. In the stationary case, the maximum stress increase occurs at the pile-soil contact and reduces with distance to negligible values at about four pile diameters away from the pile face. In the transient case, compressional stresses reach a maximum magnitude at 10-15 cm from the pile face. This indicates that compressional stresses maximize as a combination of thermal expansions of the pile and heated soil zone. The progressive increase of temperature and consequent thermal expansion of the soil results in larger compressional stresses. Furthermore, the radial stress increase in plane strain (Fig. 8.b,d,f) is higher than the stress increase in plane stress (Fig. 8.a,c,e). The compressional stresses in plane strain are increased as a result of the Poisson effects and constrained deformations along the out-of-plane direction.

For the transient case, it may seem rather contradictory that compressional stresses develop around a zone where total strains are extensional within the soil. We interpret that compressional stresses develop as a result of the blocked strains similar to compressional stresses that would develop within a heated solid bar with imposed fixities. In other words, the observed extensional strains are smaller compared to what they would have been, had they not been constrained due to the kinematics of the pile-soil interaction.

Fig.9 presents the temperatures induced radial stresses on the pile face for a range of soil moduli. In plane stress, the pile can expand freely in the out-of-plane direction (longitudinal pile deformations), therefore the additional degree of fixity induced by soil thermal expansion does not increase the radial stress in the pile (Fig. 9, solid lines). In plane strain, the resulting contact stresses that develop at the pile face are higher than those in plane stress due to the Poisson effects, as a result of the constrained deformations along the out-of-plane direction. Furthermore, the increase in contact pressure is higher in the transient analysis due to the thermal expansion of the soil (Fig. 9, dashed lines). For typical soil modulus values, the additional lateral stresses that develop at the soil-pile contact do not exceed 15 kPa at the end of 12 hours of heating. These results indicate that the heating-induced radial stresses applied by the soil on the pile remain at values that would not have a significant effect on shaft resistance. Consequently, the effect of increased radial stresses applied to the pile due to thermal dilation would not have a significant effect on load-displacement behavior, should the pile be floating (plane stress) or fixed at the top and bottom (plane strain). The higher increases in contact pressure noted in the Finite Element Analysis correspond to stiffer and stronger soils (Fig.9). For typical values of friction coefficients at pile-soil interface, these increases in contact pressure would only slightly increase the pile-soil interface strength by 2 kPa or less for soft soils, and by 5 kPa or less for medium to stiff soils. In proportion, tbe contribution of heating to shaft resistance would be relatively small. We can conclude that thermal expansion of a heat exchanger pile induces small strains and this results in small magnitude stresses with minimal soil resistance. These findings from numerical analyses are in agreement with pressuremeter experiments, which show that much higher strains are necessary to develop large stresses around an expanding cylindrical element (Briaud 1992).

CONCLUSIONS

Temperature changes induced by heat exchange operations can result in a variety of thermo-hydro-mechanical processes that can influence the serviceability and limit state of heat exchanger piles. Processes such as pore pressure development and thermal consolidation in soft saturated clays as well as thermally induced moisture migration followed by increased effective stress in unsaturated soils may play a role in pile behavior in response to increased temperatures. This letter examines the effect of thermally induced lateral stress increase as a possible mechanism that can affect shaft resistance and load-displacement behavior of heat exchanger piles. Although the Finite Element analysis presented herein is very simple (2D plane stress and plane strain models), the results indicate that the increase of contact pressure induced by the radial thermal expansion of the pile is small in magnitude and therefore would not result in significant increases in shaft resistance. It is rather unlikely that temperature induced radial expansion of the pile would increase pile capacity significantly, due to the minimal change in contact pressure at the pile-soil interface. A quantitative assessment of the impact of temperature-induced interface effects and resulting pile capacity changes is underway.

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Table 1.
Pile load at various head displacement/diameter ratios for different loading cases

Table 2.
Summary of small-scale experimental studies investigating the temperature effects on load-settlement behaviour of heat exchanger piles

Table 3.
Material parameters used in the Finite Element simulations

Fig. 1.
Load-settlement curves in prototype scale for energy piles tested at different temperatures using reduced scale models in the centrifuge (adapted from McCartney and Rosenberg, 2011)

Fig. 2.
Sketch showing the mechanical implications of heating a pile in: free, fixed and real conditions (embedded in elastic soil)

Fig. 3.
Mesh adopted in the Finite Element analyses with a total of 17,338 elements

Fig. 4.
Radial deformation of the pile and of the soil close to the interface (stationary plane stress analysis), assuming a wide range of elastic moduli for the host medium (realistic soil undrained Young's moduli are between $5x10^3$ kPa and 10^5 kPa). Note: in all cases, the thermo-elastic strain is 0.0001, which corresponds to a purely thermo-elastic response in the absence of any soil restraint. Total strains and elastic strains at the soil side are identical because the thermo-elastic strains in the soil are equal to zero for the stationary analysis with $\Delta T = 0$ in the soil.

Fig. 5.
Radial stress mobilized at the pile/soil interface in the stationary plane stress analysis, for a wide range of soil elastic moduli (realistic soil undrained Young's moduli are between $5x10^3$ kPa and 10^5 kPa). Stresses computed numerically upon pile heating (solid lines) match the stresses computed using the cavity expansion theory (circles). Pile face displacements from the numerical analyses applied on the cavity wall. Radial stress acting on the pile at full fixity is 3529kPa.

Fig. 6.
Radial distribution of temperatures at different times of the transient analysis.

Fig. 7.
Strain vs. radial distance for the stationary and the transient models: (a) Plane-strain model, s_u = 25, 50, 100kPa; (b) Plane-stress model, 25, 50, 100kPa. Note: the same results were obtained for the three soil strengths studied.

Fig. 8.
Stress vs. radial distance for the stationary and the transient models: (a) (c) (e) Plane-strain model, s_u = 25, 50, 100kPa, respectively; (b) (d) (f) Plane-stress model, 25, 50, 100kPa, respectively.

Fig. 9.
Radial stresses at the pile face for plane stress and plane strain cases from the stationary and transient analyses ($T_{initial}$ = 15°C and T_{final} = 25°C).

Table 1
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Table 1. Pile load at various head displacement/diameter ratios for different loading cases

Loading case	Head displacement/Diameter (%)	Pile load (kN)	Change in pile load[a] (%)
ΔT=0°C	1	1066	–
	2	1350	–
ΔT=29°C	1	1351	+27
	2	1622	+20
ΔT=41°C	1	1691	+59
	2	1799	+33

[a] Change in pile load with respect to ΔT=0°C loading case at the respective head displacement

Table 2
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Table 2. Summary of small-scale experimental studies investigating the temperature effects on load-settlement behaviour of heat exchanger piles

Study	Model	Soil type	Pile	ΔT (°C)	Remarks
McCartney and Rosenberg (2011)	Centrifuge (24g)	Bonny silt (compacted) w=13.2% fines=84% PI=4 ϕ'=32°	Concrete D=76.2mm (1.8m) H=381mm (9.1m)	29 / 41	40% increase in side shear resistance with heating
Wang et al. (2011)	Laboratory (1g)	N50 Fine sand (loosely compacted – 10 layers) C_u=1.47 C_c=1.21 w=0.5%	Steel tube D=25.4mm t=1.2mm *Pile surface is coated with a layer of N50 fine sand using epoxy resin*	20	50% decrease in side shear resistance with heating
		300WQ Silica flour (loosely compacted – 10 layers) C_u=4.8 C_c=2.13 w=21.5%, 24%			10% to 50% decrease in side shear resistance with heating
Wang et al. (2012)	Laboratory (1g)	N50 Fine sand (loosely compacted – 10 layers) C_u=1.47 C_c=1.21 w=0%, 2%, 4%	Steel tube D=25.4mm t=1.2mm *Pile surface is coated with a layer of N50 fine sand using epoxy resin*	20 / 40	w=0% – No change in side shear resistance w=2%, 4% – Reduction in side shear resistance
Goode et al. (2014)	Centrifuge (24g)	Dry Nevada sand D_r=60% e=0.75 D_{10}=0.09mm D_{30}=0.11mm	Concrete D=63.5mm (1.5m) H=342.9mm (8.2m)	7 / 12 / 18	No change in ultimate capacity with heating

		D_{60}=0.16mm ϕ=35° G=30MPa v=0.3			
Kramer and Basu (2014)	Laboratory (1g)	Dry F50 Ottawa sand (fine silica sand) (air pluviation) e_{max}=0.78 e_{min}=0.48 D_{50}=0.28mm C_u=1.8 G_s=2.65	Concrete D=100mm H=1.22m	20	Slight increase in pile capacity (~5%) with heating Decrease in pile head stiffness with heating

Table 3
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Table 3. Material parameters used in the Finite Element simulations

Parameter / Material	Reinforced concrete	Soil
Mass density (kg/m^3)	2500	1500
Young's modulus (MPa)	30000[a]	1000 × s_u [b]
Poisson's ratio	0.150	0.495
Thermal conductivity (W/m·K)	1.5	2.0[c]
Specific heat capacity (J/kg·K)	1200	1500[d]
Coefficient of thermal expansion (*με*/K)	10[e]	50[f]
Undrained shear strength, s_u (kPa)	–	25 / 50 / 100[g]

[a] In several studies, Young's modulus of concrete has been reported as 29 GPa (Kramer and Basu, 2014), 29.2 GPa (Knellwolf et al., 2011) and 40 GPa (Bourne-Webb et al.. 2009).
[b] Ranjan and Rao (2006) expressed the correlation of undrained Young's modulus to undrained shear strength as E=(750-1200) × s_u for normally consolidated clays (1500-2000)×s_u for OC clay similar to the ranges given in Jardine et al. (1984).
[c] Thermal conductivity of clays are in the range of 0.15-2.5 W/(m·K) with saturated clays at the higher end of this range (Al-Khoury, 2012, p.15)
[d] Specific heat capacity of clays are in the range of 920-2200 J/(kg·K) (Al-Khoury, 2012, p.15)
[e] Thermal expansion coefficient of reinforced concrete has been reported as 8.5 *με*/K by Bourne-Webb et al. (2009) and 10 *με*/K by Knellwolf et al. (2011) and Salciarini et al. (2013).
[f] Thermal expansion coefficient of clays has been reported as 30 *με*/K (Salciarini et al., 2013) and 50 *με*/K (Mitchell and Soga, 2005).
[g] Typical values of undrained shear strength selected to present detailed results for soft (12.5-25 kPa), medium (25-50 kPa) and stiff clay (50-100 kPa), respectively (*Lambe and Whitman 1969,* Terzaghi et al., 1996, p.22).

Figure 1
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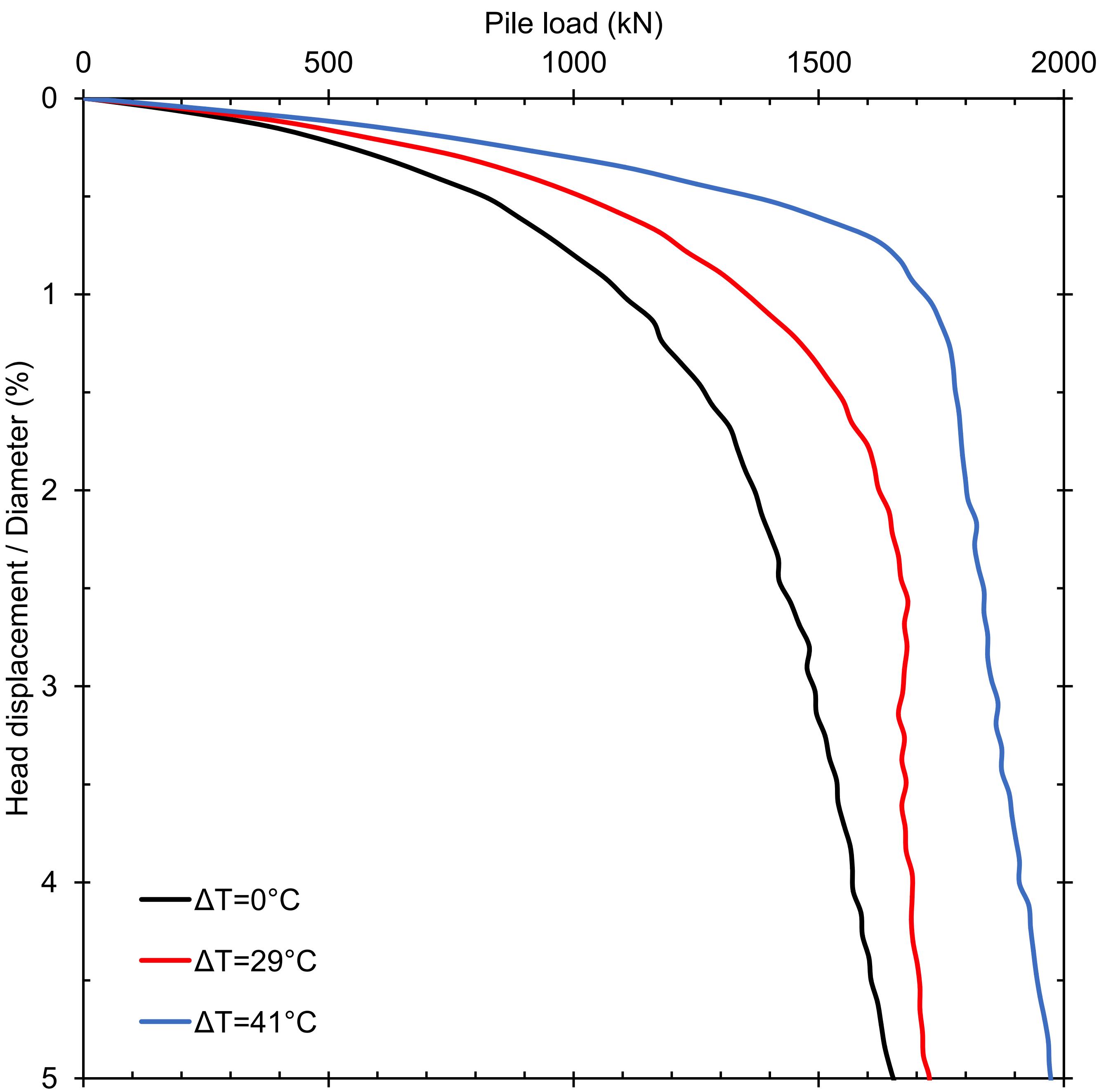

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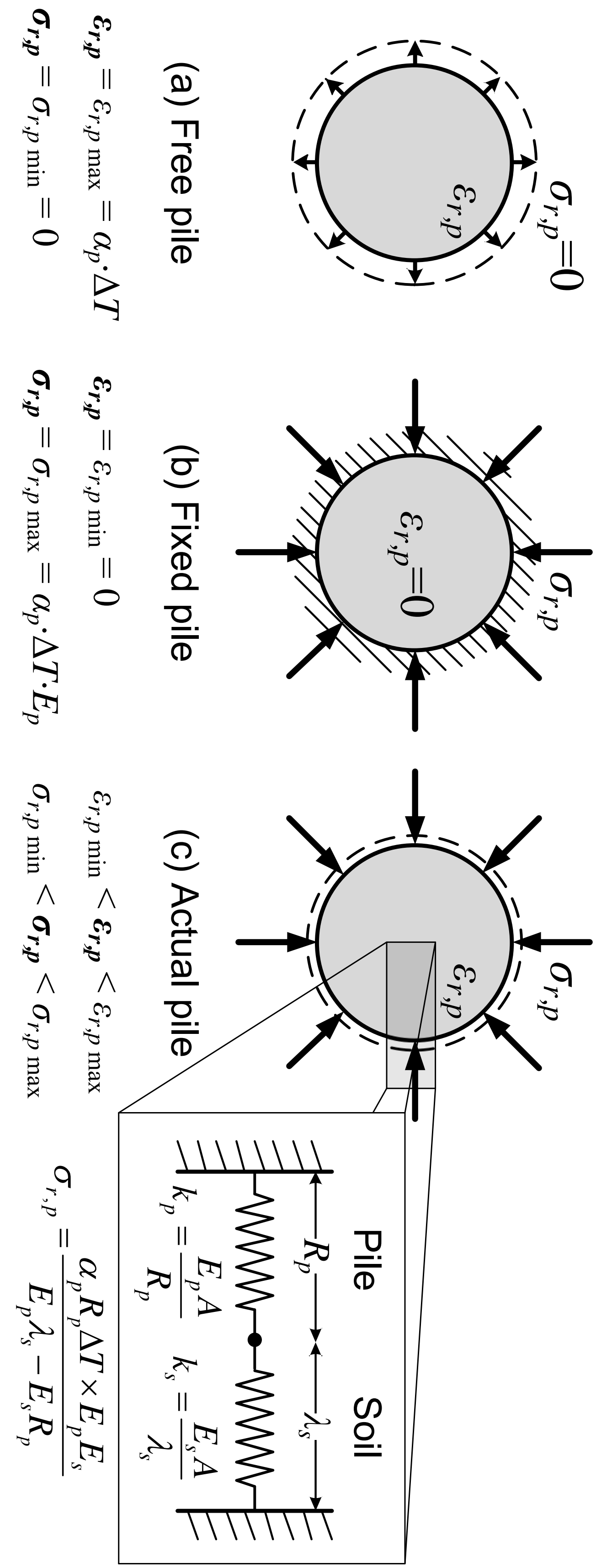

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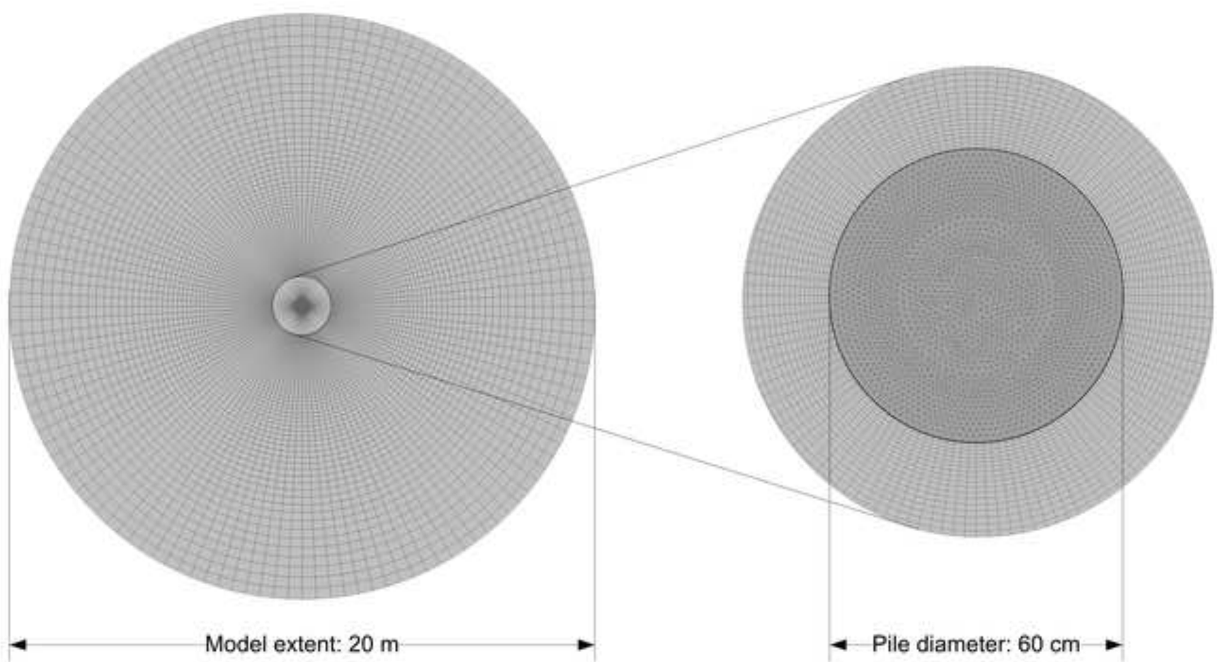

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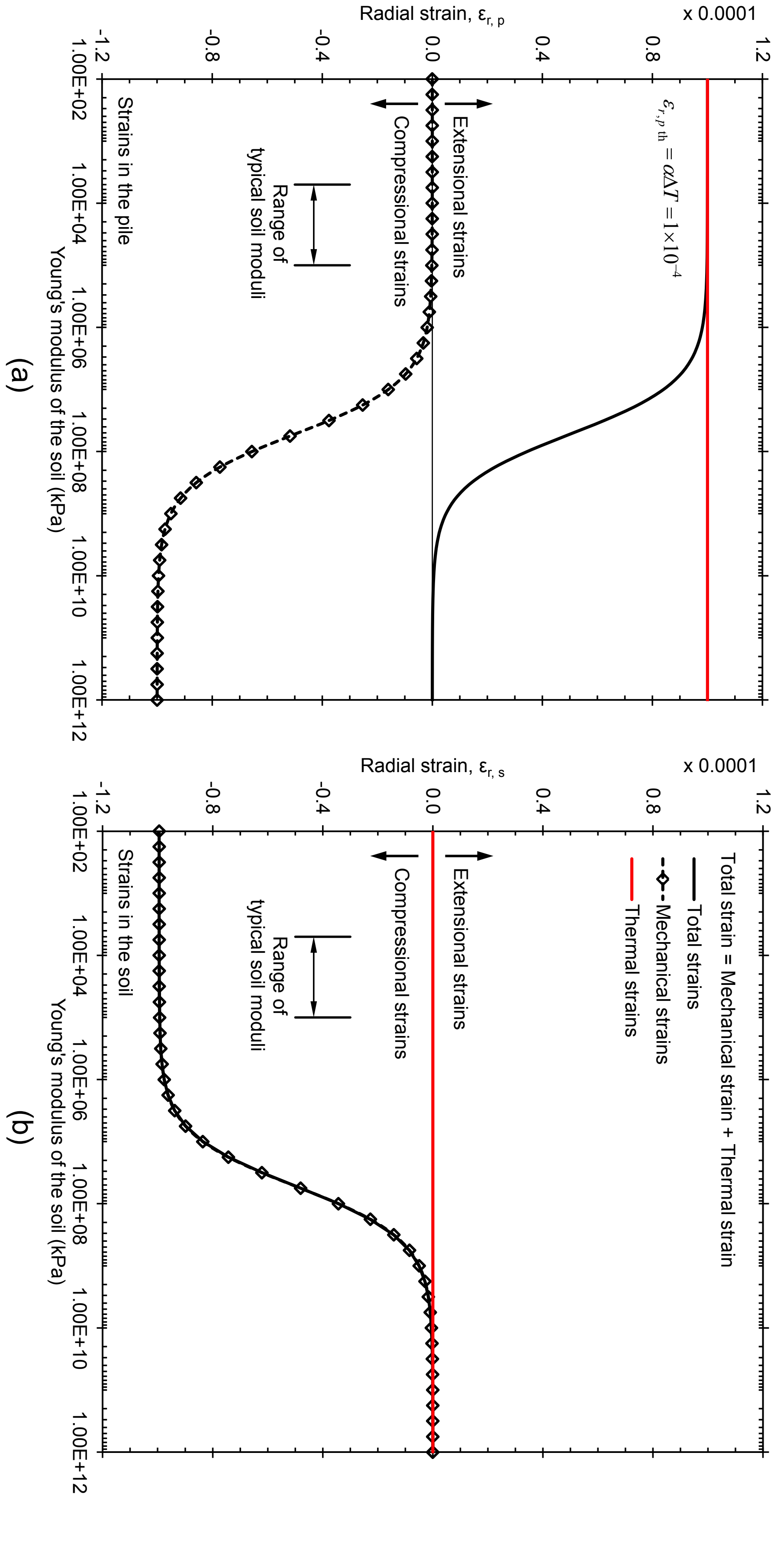

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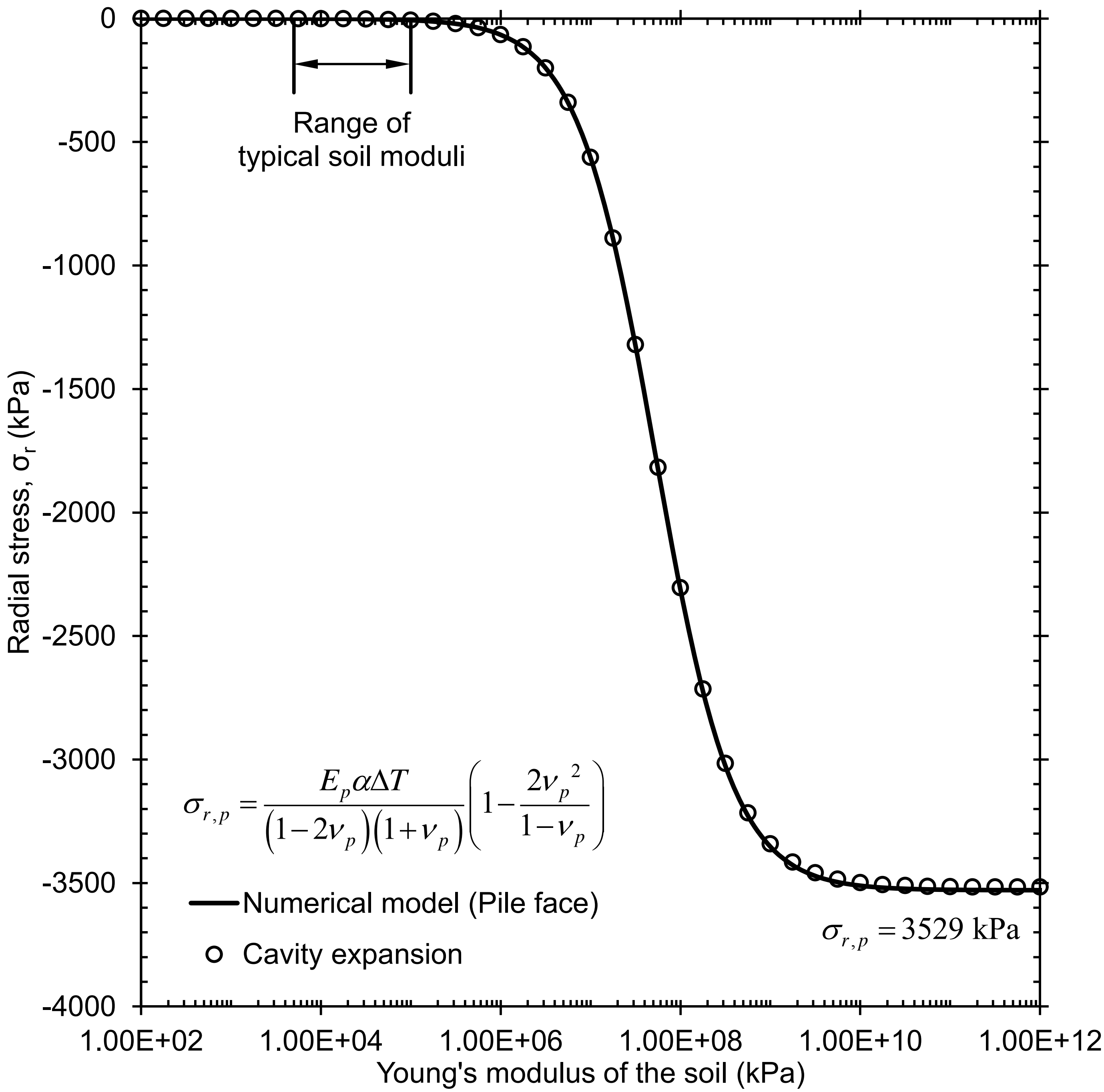

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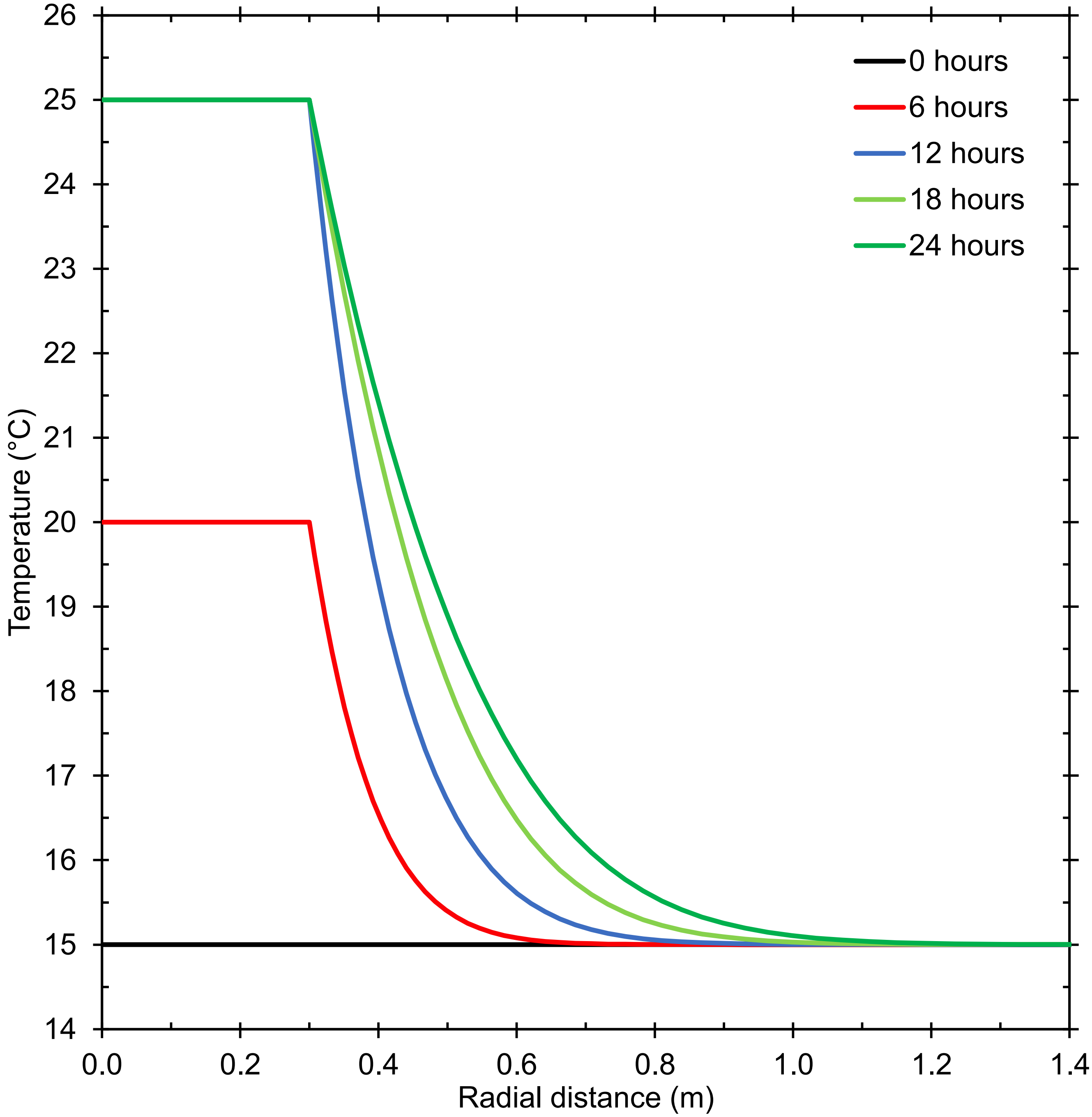

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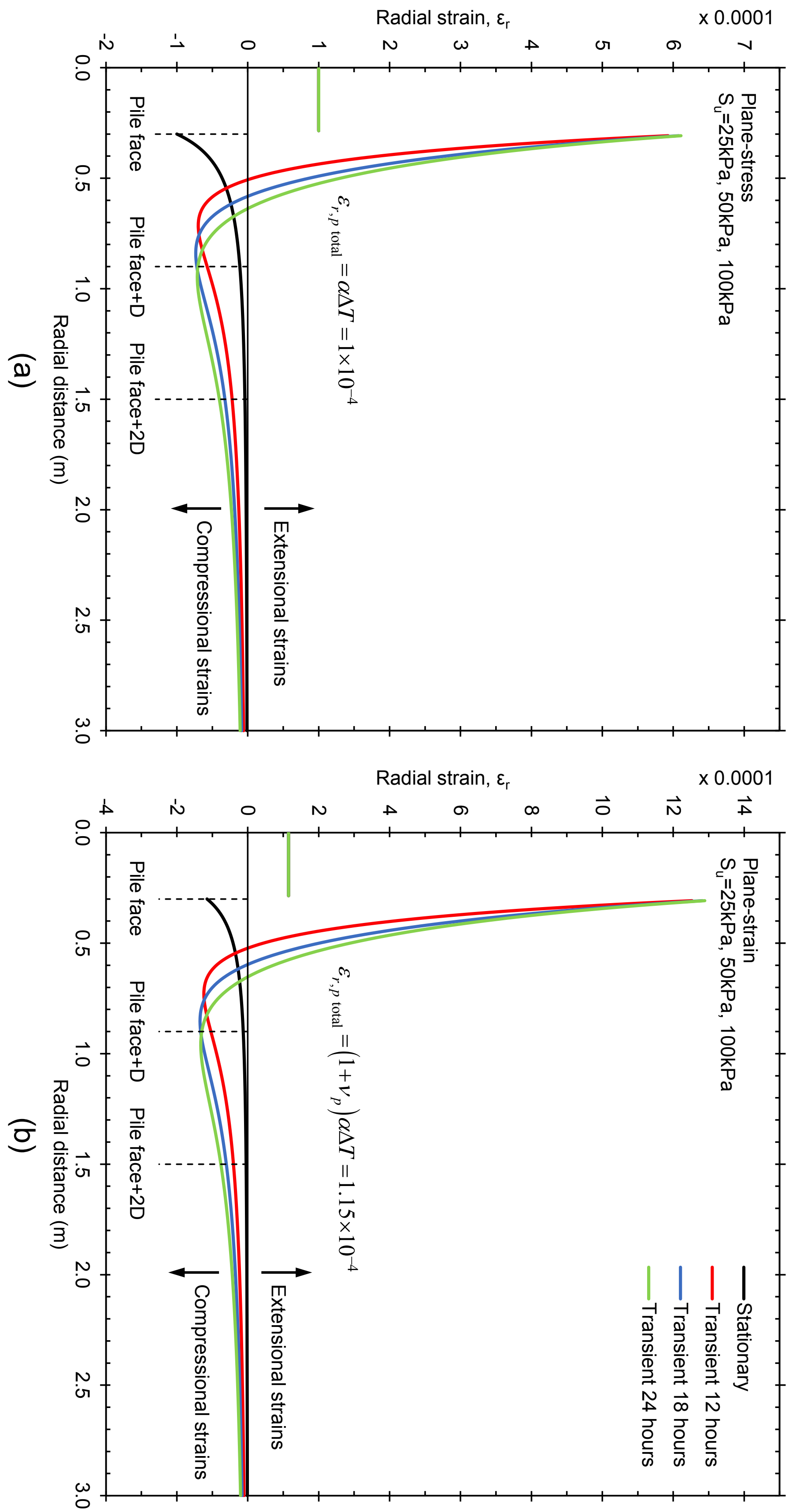

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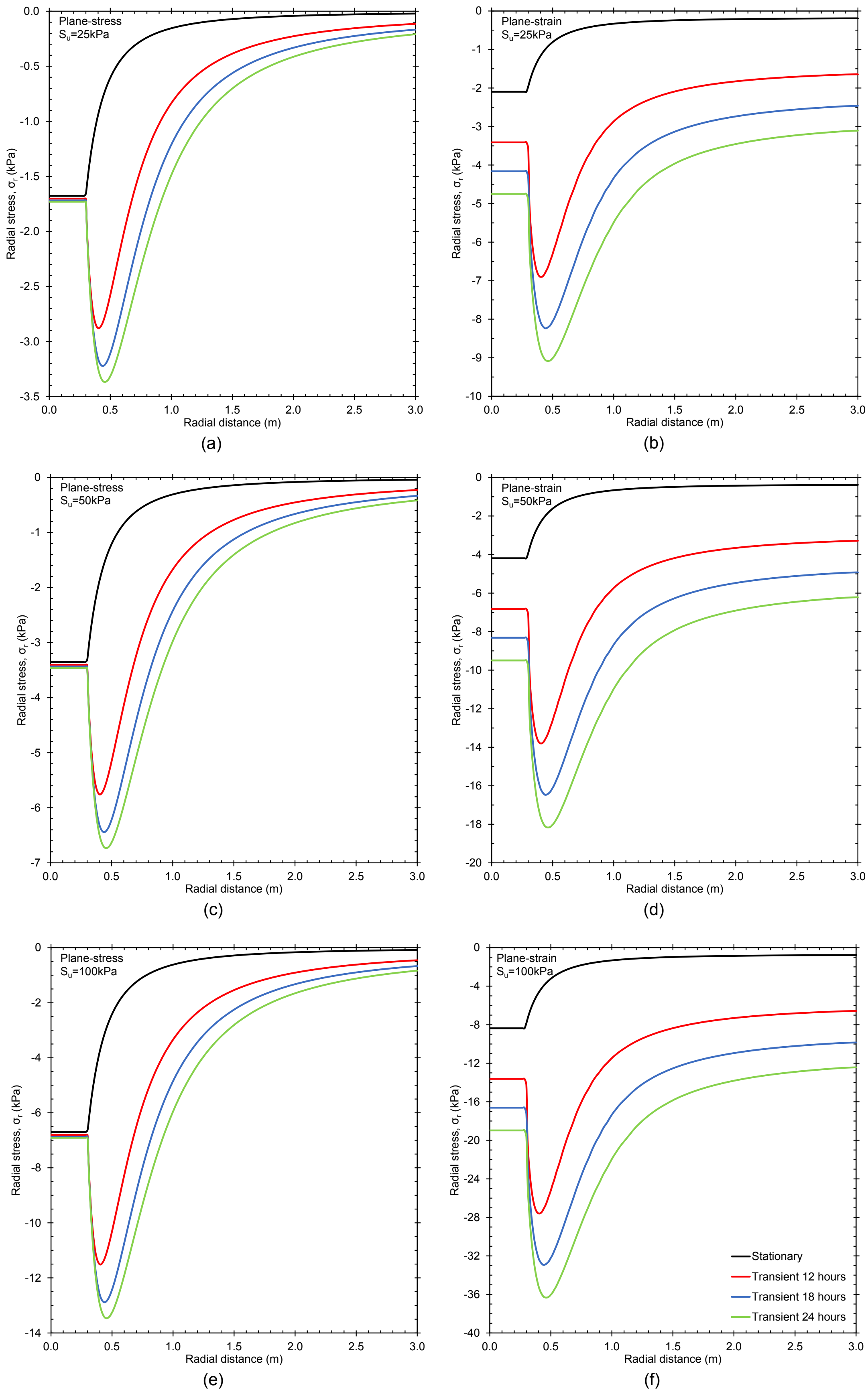

Figure 9
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