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A review on the thermo-hydro-mechanical response of soil–structure interface for energy geostuctures applications

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1. Introduction

The undeniable climate change impacts, the increasing energy demand, and the limited fossil fuel resources make searching for new sustainable clean energy resources a must for the global community.1,2 As a primary energy source, fossil fuel consumption has dramatically increased greenhouse gas (GHG) emissions since the industrial revolution, exacerbating climate change challenges.2 According to optimistic and pessimistic projections, carbon dioxide concentrations are estimated to have been less than 400 ppm in 2000, rising to 450 ppm or even more than 1000 ppm by the end of the century, respectively.2 Therefore, it is agreed to reduce GHG emissions in the Paris,3 ensuring a balance between emissions and removals after 2050. In this regard, employing energy geostuctures as a practical approach for global energy transition is vital to limit emissions by utilising renewable and clean ground energy sources.

The operation of conventional geostuctures as heat exchangers is associated with heat transfer in the surrounding soil, leading to variations in water properties and water flow in the soil pores.3 As a result, temperature and water content vary simultaneously at the interface, emphasising the importance of understanding the thermo-hydro-mechanical (THM) behaviour of the soil and the soil-geostructure interface.4,5 The non-isothermal shear behaviour of soil–structure interface with fixed but different water contents has been studied to some extent by Refs. 7, 8. However, the change in water content during the tests made it impossible to fully understand the coupled impact of temperature and water content. In the former study, for instance, the higher shear strength at elevated temperatures could not be explained by only the heating effect, whereas a drop in water content from 28.24% to 18.45% occurred upon heating from 24 to 60 °C.7 Even though further efforts are still necessary to perform tests that capture the coupled effect of temperature and water content, two different groups of studies have investigated temperature and water content impacts independently.

The significance of studying the hydro-mechanical behaviour of the soil–structure interface was first highlighted by the use of mechanically stabilised earth walls and reinforced soil slopes in contact with unsaturated soil.9 Then, energy geostuctures imposing different temperatures on the adjacent soil necessitated taking temperature into account.10 Most studies on soil–structure

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interface behaviour have initially focused on the isothermal behaviour of the interface in either a completely dry or saturated state. In these studies, soil properties such as soil type, plasticity index, particle and physical properties, as well as the initial state of the sample, such as void ratio, relative density, and moisture content, were identified as influential parameters. Furthermore, parameters such as normal stress, rate of shearing, and drainage conditions have also been introduced as determining variables. Among these parameters, normal stress is controlled by the thermal and hydraulic deformations of the surrounding soil. Thus, the volume change of the interface should be considered to accurately analyse the shear behaviour of the interface. However, studies that examined normal stress variations with temperature have found no significant effects due to the limited thermal deformations observed. Therefore, in non-isothermal conditions, the normal stress and, consequently, the shear strength of the interface is modified only by the shearing deformation. On the other hand, while matric suction does not significantly affect the thermal deformation of soils, hydraulic loading can lead to pronounced volumetric deformations. Therefore, increasing or decreasing matric suction may result in a higher or lower effective normal stress, taking the volumetric deformation of the soil into account.

The properties of the counterface material have also been introduced as additional parameters determining the shear behaviour of the interface. For a soil–structure interface with varying surface roughness, different shear failure mechanisms and thus different interface shear strengths can be observed. Furthermore, even the type of structural material (e.g., concrete, steel, or aluminium) might have an impact on the interface response during the shearing stage. In the study of Ref. 11, soil in contact with smooth steel showed a lower friction angle and adhesion compared to the one in contact with smooth concrete. Therefore, as most studies have investigated the shear response of pure sand-structure or pure clay-structure interfaces, further research on sand-clay mixtures in contact with varying structural materials is necessary to fully understand soil-geostructure interface behaviour in practice.

The effect of surface roughness on interface shear behaviour is not limited to shear strength alone. For instance, sliding along the smooth interface of coarse-grained soil in contact with the structural material accounts for a significant portion of particle displacements, while a combination of sliding and ploughing occurs for the rougher interface. This behaviour is also confirmed for the fine-grained soil–structure interface (e.g., saturated lean clay-geomembrane interface and saturated kaolin-concrete interface), where the rough interface showed more pronounced volumetric deformation when sheared. Moreover, the thickness of the interface (i.e., the thickness of the shear band) is determined by roughness alongside void ratio and water content, affecting the volumetric response of the interface during the shearing stage.

Several studies have examined the impact of matric suction and temperature on the shear behaviour of the soil–structure interface independently. This state-of-the-art paper brings together the experimental findings of these studies on the response of soil-structure interface in different TMH states, followed by the synthesis of the latest experimental outcomes in this field. In this regard, the effect of matric suction on adhesion and friction angle is investigated, with the surface roughness (i.e., smooth, medium-rough, or rough) and structural material type taken into account (i.e., steel or other materials). A detailed investigation is carried out, including recently published experimental data, to determine the impact of temperature increase or decrease on the shear strength parameters, considering the soil type (i.e., coarse-grained or fine-grained soils). This study examines, in general, the evolution of the peak shear strength (P) parameters with matric suction as well as both peak and residual shear strength (U) parameters with temperature. Finally, the shear strength variation with matric suction at room temperature and with the temperature at saturated state (unless otherwise stated) is studied. This section examines the non-isothermal shear response of the soil–structure interface with different most recent stress histories of mechanical loading, addressing the role of thermal deformation in determining shear strength. As a reference to the interface behaviour, the shear behaviour of the corresponding fundamental soil is studied in each section, and the potential underlying mechanisms affecting the thermo-hydro-mechanical behaviour of the interface are discussed.
2. Adhesion variation with matric suction and temperature

The Mohr–Coulomb failure criterion using the effective stress state has been widely used to capture the shear strength of saturated soils at room temperature. Experimental studies over a wide range of suction values have shown a non-linear variation in soil shear strength with respect to matric suction. In this regard, several equations are proposed to determine the shear strength of partially saturated soils, which among the equation shown below is proposed by Ref. 46 as a simple and practical model based on the soil–water retention curve (SWRC):

\[ \tau_f = c' + (\sigma_n - u_n) \tan \phi' + (u_a - u_{af}) \left( \frac{(\theta - \theta_u)}{\theta_t - \theta_u} \right) \tan \phi'/ \quad (1) \]

where \( \tau_f \) is the shear strength on the failure plane at failure of an unsaturated soil; \( c' \), also referred as “effective cohesion”, is the intercept of the “extended” Mohr–Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero; \( (\sigma_n - u_n) \) is the net normal stress state on the failure plane at failure; \( (u_a - u_{af}) \) is the matric suction on the failure plane at failure; \( \phi' \) is the angle of internal friction associated with the net normal stress state variable; \( \theta \) is current volumetric water content; \( \theta_t \) is residual volumetric water content; and \( \theta_u \) is saturated volumetric water content.

The equation presented by Ref. 47 was modified by Ref. 48 to reflect this non-linearity in the interface shear strength. The modified equation was then validated by direct shear tests carried out on Minco clay–steel interface with matric suction ranging between 0 and 100 kPa:

\[ \tau_f = c_a' + (\sigma_{af} - u_{af}) \tan \delta' + (u_{af} - u_{af}) \left( \frac{\theta - \theta_u}{\theta_t - \theta_u} \right) \tan \delta'/ \quad (2) \]

where \( \tau_f \) is the shear strength on the failure plane at failure of an unsaturated interface; \( c_a' \) is the effective adhesion intercept for the interface; \( (\sigma_{af} - u_{af}) \) is the net normal stress on the failure plane at failure; \( (u_{af} - u_{af}) \) is the matric suction on the failure plane at failure; and \( \delta' \) is the interface friction angle with respect to net normal stress.

As shown in Fig. 1, apparent cohesion (\( c \)) and apparent adhesion (\( c_a \)) increase with matric suction. In Fig. 1(a), apparent cohesion is determined considering the contribution of matric suction via the below equation:

\[ c = c' + (u_a - u_w) \left( \frac{\theta - \theta_u}{\theta_t - \theta_u} \right) \tan \phi' \quad (3) \]

Experimental evidence suggests that the value of \( c' \) is the same for many soils in both saturated and unsaturated conditions. However, a nonlinear variation of \( c \) with matric suction is observed for matric suction beyond the air-entry value. This nonlinear behaviour may be explained by the nonlinear nature of the SWRC caused by variations in the interfacial area between air, water, and solid particles. Therefore, the final value of apparent cohesion is controlled by SWRC, as well as potential variations in friction angle. By increasing matric suction up to the air-entry value, \( \theta \) remains equal to \( \theta_t \), and apparent cohesion varies linearly with matric suction. As the air-entry value is passed, air enters the pores and \( \theta \) decreases with matric suction nonlinearly. Thus, the rate of increase in apparent cohesion with matric suction decreases. The potential variation in friction angle with matric suction and its subsequent impact on apparent cohesion will be discussed later.

Although apparent adhesion variations are also explained by matric suction, surface roughness plays a paramount role in adhesion determination. The normalised roughness \( R_n \), defined in Eq. (5), is commonly used to identify roughness in studies involving granular soils:

\[ R_n = R_{max}/D_{50} \quad (4) \]

where \( R_{max} \) is the maximum vertical distance between the highest and lowest peaks of the structure asperities over a fixed length. The roughness of the clay-structure interface can also be described by the average surface roughness \( R_s \), which is determined by the average deviation of the profile from its mean line.

As adhesion is dependent on the structural material and surface roughness, the evolution of adhesion with matric suction is studied more in detail in Fig. 1(b) and (c) by taking the type of structural material into account (e.g., steel or non-steel materials). In Fig. 1(b) and (c), “S”, “M”, and “R” stand for smooth, medium rough, and rough interface, respectively. An interface with higher roughness usually shows higher adhesion since the contact area between the soil and the solid asperities increases with roughness. However, this impact appears to be independent of the structural material, as shown in Fig. 1(c). Nonetheless, observed higher adhesion for CDG soil in contact with medium-rough steel than with a rough interface. Water migration during the shearing process was monitored as a potential underlying mechanism, and higher water migration from the sample was identified for the rough interface at the same suction. Therefore, the higher \( \theta \) led to higher adhesion for the medium-rough interface. Furthermore, a higher adhesion was observed for the smooth interface compared to the rough one in the saturated condition by Ref. 48. The role of physical–chemical bonding between the smooth steel surface and soil was considered as the fundamental mechanism to explain this phenomenon. Adhesion is largely undisturbed at yielding for the smooth interface, as yielding and failure occur almost simultaneously at a much lower shear displacement. Contrarily, for the rough interface, due to slippage and grain rearrangement occurring after yielding and before reaching the peak shear stress, such bonding can be significantly destroyed along the failure plane, leading to lower adhesion.

Comparing samples following different hydraulic paths reveals a more evident change in apparent cohesion and apparent adhesion of samples subjected to suction hysteresis. The mechanical behaviour of unsaturated soils is affected by matric suction and water content; thus, it is strongly dependent on the hysteresis of the SWRC. In Eq. (3), the effective cohesion and matric suction will remain identical for different paths of SWRC. However, due to the hysteresis phenomenon, the volumetric water content is lower following the wetting path than the drying path. Therefore, the overall value of apparent cohesion will be higher following the drying path than the wetting path. Conversely, an overall increase in apparent cohesion and subsequently in apparent adhesion was observed following the wetting path compared to the drying path in the study of Ref. 50 on an artificial fine sandy silt-steel interface. This phenomenon was attributed to the soil type, where water may act as a lubricant and the cyclic suction stress results in hardening. A more in-depth examination of the isothermal and non-isothermal behaviour of the partially saturated soil–structure interface, including different types of interfaces, in different SWRC paths, is necessary to understand the effect of hydraulic hysteresis on interface behaviour.

The influence of temperature on cohesion is investigated in Fig. 2(a). In this figure, both increasing and decreasing trends can be observed. Unlike the other studies conducted on saturated samples, Xiao et al. investigated the effect of contradictory trends are observed, as well. FIG. 2(b) presents data corresponding to residual shear strength to examine the temperature impact on adhesion in large displacements, while the temperature impact on adhesion in small displacements is investigated in Fig. 2(c).

Adhesion at the interface is induced by soil–solid contact through a thin water film that is present at the interface.
Fig. 1. Variation in (a) apparent cohesion, (b) apparent adhesion of soil–steel interface, and (c) apparent adhesion of soil-non-steel interface with matric suction. 

For unsaturated interfaces, the water meniscus developed at the contact point leads to water tension. Conversely, saturated interface adhesive behaviour is governed by a rate-dependent viscous force. In the saturated state, the shear strength required to resist the viscous force between two circular flat surfaces can be expressed as follows:

$$F_v = \frac{16\pi R^3}{3\eta h}$$

where $F_v$ is the viscous force; $R$ is the circular flat surfaces radius; $h$ is the thickness of the thin liquid film; $\eta$ is the dynamic viscosity of thin liquid film at the interface zone; and $t_s$ is the shearing time. It is necessary to consider the temperature-dependent behaviour of dynamic viscosity and the thickness of the liquid film to determine the effect of temperature on the viscous force, defined in Eq. (6), and thus adhesion.

Liquid film thickness is controlled by the thermal volumetric behaviour of the soil, where overconsolidated soils with high OCR achieved via mechanical unloading (UOC) dilate upon heating while normally consolidated soils (NC) and overconsolidated soils with high OCR achieved via mechanical reloading (ROC) contract as the temperature increases. Thus, the elastic dilation leads to a greater, while the plastic contraction results in a smaller $h$. It is worth noting that although the ROC interface may exhibit similar characteristics to those of the UOC interface, the contractive thermal deformation due to the most recent stress history may alter the shear response at elevated temperatures, which has not been examined thoroughly to date.

The dynamic viscosity of water decreases linearly with temperature, as proposed in Eq. (7). Even though the temperature dependence of the viscosity of the thin water film at the interface may differ from that of free water, this equation still provides a good understanding of the effect of temperature (in °C) on dynamic viscosity (in Pa s).

$$\eta (T) = -0.00046575 \times \ln (T) + 0.00239138$$

The interplay between $d\eta/dT$ and $dh/dT$ determines the temperature impact on adhesion. At lower temperatures, the increase in $\eta$ and the decrease in $h$ upon elastic contraction may lead to a slightly higher adhesion than that at room temperature. The potential transient undrained condition (i.e., rapid heating/cooling or shearing), generating excessive pore water pressure, also appears to play a role, with the kaolin–steel interface exhibiting no significant change in adhesion upon cooling.

It is more challenging to address the temperature impact on the adhesion of the heated interface as $h$ is determined by the thermal deformation of the interface (i.e., plastic contraction of the NC and ROC interfaces or elastic expansion of the UOC interface), while $\eta$ decreases with temperature. The tests conducted on the NC Illite-concrete interfaces showed an increase in adhesion from 4 kPa to 12 kPa upon heating from 20 °C to 50 °C, indicating a greater $dh/dT$ than $d\eta/dT$. The temperature seems to have no effect on the adhesion of the red clay-porous stone interface, as $d\eta/dT$ is almost equal to $dh/dT$. This explanation seems invalid for the NC kaolin-concrete interface heated from 24 to 34 °C, showing a loss of adhesion. In this case, an altered interface microstructure due to the high heating rate (i.e., 7 °C/h) and a higher Columbian repulsion between negative double layers, leading to a weakened solid–solid contact, may have resulted in a lower adhesion, which needs to be investigated more in detail.

The same explanation is also valid in explaining the observed effect of temperature on cohesion. For the UOC interface, as soil dilates thermally at elevated temperatures, $h$ increases, leading to lower cohesion. Conversely, the expected thermal contraction of the NC interface upon heating would decrease $h$, resulting in higher cohesion.
3. Friction angle variation with matric suction and temperature

The friction angle of soil is determined by a number of factors, the most important of which are density, grain size distribution, angularity, and particle interlocking. As shown in Fig. 3, regardless of the type of structural material, surface roughness also plays a vital role in determining the friction angle of the soil-structure interface, with higher roughness resulting in a higher friction angle. Furthermore, water content variations at the interface can lead to a change in the friction angle by affecting one of the factors listed above, with Fig. 3 showing that the apparent friction angle will remain either constant or increase with increasing matric suction for the soil and soil-structure interface. For instance, Hossain and Yin observed that friction angle, and thus shear strength of the CDG soil and the soil-cement interface, varies with matric suction. The effect of matric suction on the soil volumetric behaviour was assumed as a potential root cause. In this regard, the shear-induced soil dilation was used to assess this impact, with the following equation being employed to account for the effect of soil dilatancy on friction angle:

\[
\phi = \phi' + \psi \quad (7)
\]

where \(\phi\) is the apparent friction angle; and \(\psi\) is the dilatancy angle.

The soil dilatancy is at its peak, particularly under higher matric suction and lower normal stresses (i.e., higher OCR), for a surface with a higher roughness. For instance, the outcomes of the studies on CDG soil show an initial compression followed by an eventual dilation until the peak shear stress is reached. This dilative behaviour is more pronounced for the samples tested at higher suction and lower normal stresses, leading to a greater apparent friction angle. This phenomenon can be attributed to water content decrement as matric suction increases, where the soil–structure becomes stiffer, and the particles move up or over each other rather than around each other. On the other hand, friction angle was found to be a matric suction-independent parameter for the Minco silt–steel interface and the corresponding fundamental soil, which can be attributed to the contractive or slightly dilative volumetric behaviour during the shearing stage.

Furthermore, as shown in Fig. 3(c), Hassanikhah et al. conducted a series of suction-controlled interface direct shear tests on the soil-geomembrane interface to investigate the effect of surface roughness on friction angle. In that study, the textured geomembrane interface showed a higher apparent friction angle than the smooth one for identical stress histories (i.e., same matric suction and net stress). This observation was compatible with the volumetric behaviour of the interfaces, where the textured geomembrane interface dilated more significantly.

Friction angle variation with temperature for both soil and soil–structure interface are presented in Fig. 4. In general, the temperature has an insignificant impact on soil friction angle. As shown in Fig. 4(a), the friction angle obtained for Fontainebleau and Quartz sand showed a temperature-independent behaviour. It is due to the temperature-independent volumetric behaviour of coarse-grained soils, which results in no thermal deformation. On the other hand, for NC fine-grained soils at elevated temperatures, a slightly higher or a slightly lower friction angle is also available. It is worth noting that in NC fine-grained soils, no post-peak softening resulted in identical shear strength corresponding to small and large displacements (residual and peak values).

Similar to coarse-grained soils, an insignificant temperature impact is observed for the coarse-grained soil–structure interface, as shown in Fig. 4(b). Furthermore, water does not appear
Fig. 3. Variation in (a) apparent friction angle of soil, (b) apparent friction angle of soil–steel interface, and (c) apparent friction angle of soil-non-steel interface with matric suction.

Therefore, the thermal consolidation experienced prior to shearing led to no significant impact on the interlocking asperities; and, thus, friction angle. For the UOC kaolin-aluminium interface, as the temperature increased from 40 °C to 60 °C, the volumetric behaviour changed from elastic dilation to plastic contraction, leading to modified interlocking asperities; and thus, a lower friction angle. It is worth mentioning that the $D_{50}$ of the soil (approximately 0.7 µm) and the average roughness of the counterface (approximately 0.602 µm) were comparable in this study (i.e., not an extremely huge or small roughness), which facilitated particle rearrangement at the interface. Therefore, the roughness, affecting the geometry of interlocking asperities, and the thermal deformation of the soil should be considered when addressing temperature impact on friction angle.

4. Shear strength variation with matric suction and temperature

Experimental data suggest that matric suction does not affect residual shear strength. The driving mechanism for this phenomenon is considered to be complete disruption in the air–water menisci along the failure surface. As the water meniscus starts to break, matric suction impact will be reduced to a negligible level along the shear plane, leading to a semi-identical residual shear strength for samples with different matric suction. Therefore, the role of matric suction in determining only the peak shear strength is examined in this section, whereas the non-isothermal shear strength of the soil–structure interface is discussed at both peak and residual states.

The variation in shear strength of the soil and the interface with matric suction is investigated in Figs. 5 and 6, where a significant contribution of normal stress ($\sigma_n$ in kPa) can also
be observed. As shown in Fig. 5, an increase in the peak shear strength with matric suction is observed for the fundamental soils.\textsuperscript{33,48,71,81} Fig. 6(a) investigates matric suction impact on the peak shear strength of the soil–steel interface, while the peak shear strength of soil in contact with other structural materials is studied in Fig. 6(b). As shown in Fig. 6 peak shear strength increases non-linearly with an increase in net normal stress and matric suction for interfaces with different surface roughness. The hardened soil–structure and the corresponding higher apparent yield stress are assumed to be the leading reasons for the enhanced shear strength of the soil and the interface in high suctions.\textsuperscript{71} Indeed, regardless of the studied soil or the interface, the capillary tension between soil grains increases in higher matric suctions. Thus, the soil fabric dilates in the shearing stage, increasing the angle of friction and peak shear strength.\textsuperscript{82}

The increase in shear strength is relatively minor for the interface compared to the soil, especially for the smooth interface.\textsuperscript{14} This can be attributed to the development of menisci with larger radii between the smooth surface and soil particles than the one between soil particles, which leads to lower local matric suction.\textsuperscript{48}

Shear failure might occur within the soil or at the interface as the shear force increases. The failure plane, determined by the interface material and its properties, identifies a critical roughness that can be employed to predict the failure plane. In general, shear failure occurs within the soil when the roughness exceeds the critical value, as the interface shear strength is greater than that of the fundamental soil. For the surface roughness close to the critical value, sliding, the typical shear mechanism of the smooth interfaces, and ploughing (for the coarse-grained soil–structure interface) or reorientation of clay stacks (for the fine-grained soil–structure interface), the shear mechanism commonly observed in soils, coincide. Finally, relative sliding takes place at the interface for roughness less than the critical value, revealing an elastic–perfectly plastic behaviour.\textsuperscript{15}

The critical roughness depends on the interface type and its properties. For instance, Yin and Hossain\textsuperscript{13} conducted a series of direct shear tests on CDG soil and CDG soil-rough cement interface at 300 kPa net normal stress, and varying matric suctions. For the identical roughness and net normal stress, CDG soil showed lower shear strength than the interface in the saturated state. However, as matric suction increased, soil shear strength increased more significantly compared to the interface. For matric suctions beyond 120 kPa, the interface showed lower shear strength, which was explained by the lack of water in higher matric suctions, leading to the breakage of bonding between soil and cement particles along the failure surface.\textsuperscript{13}

Borana et al.\textsuperscript{82} conducted a series of tests on the CDG soil–steel interface at three shear planes and three different matric suctions. The shear planes were designated to be 0 (INT-0), 1 (INT-1), and 2 mm (INT-2) away from the steel surface. The interface with 0 mm plane thickness showed a noticeable decrease in shear strength when compared with the soil, INT-1 and INT-2, as matric suction increased. In fact, a higher matric suction led to a shift of the shear failure plane towards the surface of the interface. Therefore, the critical shear failure plane, which represents the minimum shear strength, is shifted to the counterface surface with decreasing roughness and increasing matric suction.

The evolution of peak shear strength of the fundamental soil with temperature is shown in Fig. 7. Under a given normal load, the peak shear strength of the soil includes two components: $\tau_D$ due to the soil dilatancy and $\tau_{CV}$ corresponding to the critical state at large displacements.\textsuperscript{15} Several experiments have been carried...
The effect of temperature on the peak shear strength of the interface is examined in Fig. 8(a), (b), and (c) for coarse-grained, NC fine-grained, and OC fine-grained soils, respectively. It is generally established that the shear behaviour of the interface at different temperatures follows the same trend as the soil.

The role of temperature on the volumetric behaviour of soils should be investigated in order to address the variation in the shear strength of the interface with temperature. For the coarse-grained soil–structure interface, the thermo-elastic nature of the soil deformation leads to no hardening effect. Thus, the shear strength remains almost constant with increasing temperature. For instance, as shown in Fig. 8(a), no significant temperature impact was observed for direct shear tests carried out on the dense sand–steel interface in the temperature range of 22 °C to 60 °C.

On the other hand, the interplay between thermal softening and strain hardening controls the non-isothermal shear behaviour of the fine-grained soil–structure interface, with the most recent stress history and normal stress characterising the thermal deformation and determining the non-isothermal shearing behaviour of the interface. Lower preconsolidation stress at elevated temperatures leads to lower shear stress needed to achieve yield. Alternately, heating results in the thermal collapse of the NC and the ROC soil–structure interface, leading to a strengthened interface due to strain hardening, also known as the thermally induced apparent overconsolidation, while the UOC soil–structure interface remains in the elastic zone and does not undergo thermo-plastic deformation upon heating.

As shown in Fig. 8(b), the temperature has a significant effect on the peak shear strength of the NC fine-grained soil–structure interface, which becomes less pronounced with decreasing the normal load. In higher normal loads, higher, lower, or...
Energy geostructures couple the structural role of conventional geostuctures with that of heat exchangers, undergoing cyclic temperature variations at the soil–structure interface and within the surrounding soil. These temperature variations may also result in concurrent water migration away from and towards the geostuctures, leading to cyclic changes in the water content. Thus, understanding the impact of temperature and water content variations on the mechanical response of the soil-geostructure interface is of paramount importance to ensure the proper operation of energy geostructures. In this paper, the results of direct shear tests analysed in the framework of energy geostructures are brought together to gain a comprehensive understanding of soil and soil–structure interface behaviour in various THM states. The following are some of the conclusions drawn from the laboratory testing campaigns:

- Existing experimental data show that increasing matric suction from zero to the air-entry value tends to increase apparent adhesion linearly as the interface remains almost saturated. Once the interface desaturates beyond the air-entry value, the increasing trend becomes nonlinear. The nonlinear nature of the soil–water retention curve (SWRC) and its role in determining apparent adhesion may explain this nonlinearity. On the other hand, apparent adhesion is affected by temperature fluctuation to a lesser extent. The solid–solid contacts and the adhesive viscous force at the interface govern the evolution of apparent adhesion with temperature. The viscous force depends mainly on the dynamic viscosity of water and the thin liquid film thickness at the shear band. The elastic dilation and, thus, increased interface thickness of the UOC soil–structure interface and the decreased dynamic viscosity of water reduce adhesion. On the other hand, the interplay between the non-isothermal behaviour of dynamic viscosity and interface thickness for the NC and ROC soil–structure interfaces may lead to higher, lower, or identical adhesion at elevated temperatures.

- The evolution of apparent friction angle with matric suction can be characterised by the interface dilatancy angle at varying matric suction, leading to higher or identical friction angles. A greater matric suction may lead to a larger dilatancy angle and, thus, a larger apparent friction angle. It is worth noting that an interface with a higher roughness and lower normal stress (i.e., a higher OCR) exhibits more dilative behaviour and a higher apparent friction angle. On the other hand, the temperature impact on the interface friction angle is negligible. A coarse-grained soil–structure interface undergoes only elastic thermal deformation upon heating, resulting in an insignificant temperature effect on the friction angle. However, no consistent trend has been observed depending on the interplay between decreasing friction angle and increasing adhesion. Furthermore, as a result of elastic thermal deformation, cooling seems not to affect the peak shear strength to a great extent. It is worth noting that in the study of Yavari et al. [25], all the samples were preheated to 40 °C and pre-consolidated to 100 kPa prior to the tests. Therefore, thermal consolidation, the leading cause of temperature impact on the clay–structure interface, was negligible.

- The peak shear strength of the OC kaolin-concrete interface (Fig. 8(c)) has either remained constant [16,56] or decreased [34] upon heating. The lower shear strength of the UOC interface is attributed to the thermal softening, becoming less pronounced with increasing the OCR. The ROC interface with higher roughness has also shown a lower shear strength upon heating, with identical thermal deformation prior to the shearing to that of the NC interface. An increase in thermal energy, the root cause of bond slippage and a partial collapse of the soil structure, may explain this behaviour.

- From a practical perspective, residual shear strength and associated parameters should be considered when analysing and designing energy piles. Temperature sensitivity can be neglected in designing the coarse-grained soil–structure interface due to the elastic nature of thermal deformations, as discussed previously. The residual shear strength of the fine-grained soil–structure interface is examined in Fig. 9(a), where no significant temperature impact is observed for all interface types at low normal stresses.

- On the other hand, increasing the normal load results in a lower, higher, or identical residual shear strength at elevated temperatures. The residual shear strength seems to be affected by temperature to a lesser extent compared to peak shear strength. For instance, kaolin in contact with steel or concrete shows a greater peak shear strength at elevated temperatures, whereas the residual shear strength appears to remain identical. Cooling does not significantly affect residual shear strength, as observed for the peak shear strength.

- As shown in Fig. 9(b), the residual shear strength of the OC kaolin–concrete interface responds the same as the peak shear strength to thermal loading. The role of thermal softening, potential plastic thermal deformation and the change in thermal energy can be regarded as driving mechanisms to control the non-isothermal residual shear strength of the interface.
observed for the fine-grained soil–structure interface studied in the literature, with the non-isothermal interface friction angle depending on several factors, such as the thermal deformation of the interface, $D_{50}$, and the average size of asperities.

- The peak shear strength of an interface increases with matric suction, which can be attributed to the potential increase in apparent adhesion and apparent friction angle (induced by a dilation angle greater than zero) once the interface is desaturated. On the other hand, temperature impact on the shear strength of the interface is determined by the potential increase in adhesion and the potential reduction in interface friction angle, being more pronounced at higher normal loads. The coarse-grained soil–structure interface and the UOC fine-grained soil–structure interface with high OCR show a temperature-independent shear behaviour, primarily attributed to thermoelastic deformations. Alternatively, plastic/elastic thermal strains that occur upon heating/cooling can reduce, increase, or maintain the shear strength of the NC, ROC, and lightly UOC fine-grained soil–structure interfaces at elevated/lower temperatures.

- This paper aimed to address the possible impacts of temperature and matric suction on the shear response of the soil-geostructure interface. Yet, there are still significant knowledge gaps in fully understanding the behaviour of the soil-geostructure interface. In most studies, the THM behaviour of the soil–structure interface was examined for pure sands and clays, whereas, in most cases, the soil surrounding energy piles is a mixture of the two. In addition, the coupled impact of temperature and water content is not examined systematically, with the effect of hydraulic hysteresis being disregarded. A more detailed examination of the non-isothermal shear response of the interface under varying most recent stress histories is also necessary. Thus, to develop a comprehensive framework, further experiments should still be conducted, considering all the possible variables, THM loading paths, and soil–structure interface combinations.
Fig. 9. Residual shear strength variation with temperature for (a) the NC fine-grained soil–structure interface and (b) the OC fine-grained soil–structure interface.

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Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability
Data will be made available on request.

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