https://doi.org/10.33271/nvngu/2026-3/050

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# IMPACT OF TEMPERATURE VARIATIONS ON SOIL-FOUNDATION INTERFACE BEHAVIOR

**Purpose.** The aim of the study was to investigate the reaction of the soil-foundation interface to variations in temperature. This study examines the impact of temperature variations on the stress distribution at the foundation-soil interface, which is crucial in the presence of a heat source or in regions with considerable thermal variations.

**Methodology.** A contact and friction law using the penalty method is employed with finite element modeling of the interaction between an elastoplastic soil (Mohr-Coulomb criterion) and a rigid reinforced concrete foundation with elastic behavior. A thermomechanical coupling is considered to analyze the effects of temperature on the soil-foundation interaction, enabling a detailed study of the system's behavior under various conditions.

**Findings.** The results indicate that changes in soil temperature have a notable effect on how contact stresses are distributed at the foundation-soil interface. Such variations can influence the overall performance and stability of foundations, especially under conditions where thermal fluctuations are pronounced.

**Originality.** This work, in addition to finite element modeling of all nonlinearities (geometrical, material, and contact ones), presents the thermomechanical coupling method, which allows for precise analysis of the temperature's impact on the soil-foundation interaction, an aspect often overlooked in conventional research.

**Practical value.** The results are valuable for engineers responsible for foundation design, particularly in areas subjected to significant temperature variations, whether due to natural phenomena (such as geothermal hot water) or industrial activities (such as underground furnaces for material processing), including energy production sites. By considering thermal effects in the foundation design, it is possible to reduce risks associated with thermal changes in the soil and foundations, thereby improving the stability and longevity of the infrastructure.

**Keywords:** *footing-soil interaction, friction, temperature change, thermomechanical coupling*

Received: 25 December 2025
Accepted: 09 April 2026
Available online: 27 June 2026

**Introduction.** When evaluating the response of a structure with significant structure–foundation–soil interaction, geotechnical uncertainties can have a major impact. It is therefore crucial to identify and clearly define the key influencing factors. For instance, variations in soil stiffness or local layering can significantly modify how the foundation transfers loads to the soil, which in turn affects the overall structural response and informs critical design decisions.

In this context, several researchers have exerted significant efforts to overcome various difficulties associated with this type of problem. Without trying to present an in-depth list, we can briefly examine certain development methodologies and techniques that have led to the state of the art, as we know it today, or recent work involving the problem of footing-soil interaction.

First and foremost, an extensive variety of theoretical approaches were offered at the outset for the quantitative assessment of the bearing capacity and the stress distribution at the interface contact [1–3].

Since then, many studies have investigated the evolution of the sliding surface as eccentricity increases, showing that higher eccentricity in the applied load tends to reduce the ultimate bearing capacity of the foundation. This behavior highlights the critical role of load placement in the design and stability assessment of foundation systems [4–6]. Numerous studies in this domain have employed limit analysis to provide appropriate load-bearing capacity coefficients derived from failure mechanisms, using upper or lower limit theorems of plasticity [7–9].

To determine the real behavior of the footings when subject to a combined vertical and horizontal load torque, a vast number of experiments were conducted (Massih, D. Y. A., 2007) [10, 11].

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Other writers have explored eccentric tilting loading from both numerical and theoretical approaches [12–14].

Artificial neural networks have been used successfully to solve a variety of problems, including settlement, soil characteristics, and behavior. Comprehensive information regarding the aforementioned applications can be found in the literature [15–17].

Studies examining the effects of temperature changes on soil–foundation interfaces reveal complex behavior. In the case of sandy soils and sand–structure interfaces, thermal variations appear to have minimal influence on shear strength under both constant normal load (CNL) and constant normal stiffness (CNS) conditions [18]. In clayey soils, increasing temperatures lead to greater cohesiveness and enhanced shear strength, primarily as a result of thermal contraction during heating [18, 19]. The clay–structure interface shows a smaller increase in shear strength due to temperature changes compared to bulk clay samples, reflecting the fact that interface adhesion is inherently lower than the cohesion within the clay itself [18, 19]. In energy pile applications, field measurements indicate that soil temperature remains relatively stable at approximately 13 °C at depths below 5 meters [20]. Laboratory experiments on sand-concrete interfaces exposed to temperature cycles show that the sand undergoes only minimal contraction overall [20]. These results emphasize the need to account for thermal effects in soil–structure interactions, especially when dealing with clayey soils and energy pile applications, where temperature-induced changes can significantly influence foundation performance.

The literature study indicates that none of the published studies consider the numerical analysis of the thermal effect, namely the temperature variation on the stress distribution at the soil-sole contact. This study attempts to examine the influence of a change in the temperature of a massif due to a natural (Geothermal hot water) or industrial (Underground furnaces for wood treatment, metallurgy, pottery, and cooking) phenomenon on the response of soil-foundation interfaces.

***Thermomechanical interactions in contact problems.*** Thermomechanical coupling in soils is inherently complex, as it arises from the simultaneous interaction of thermal loading and mechanical response. Experimental and numerical investigations have shown that heating does not merely alter soil stiffness, but can also induce pronounced non-linear behavior accompanied by progressive hardening mechanisms [21]. Experimental investigations on clayey soils have shown that their response to thermal loading is strongly conditioned by stress history, exhibiting features comparable to time-dependent creep behavior rather than an instantaneous mechanical response [22]. Investigations carried out on unsaturated clayey silty sand showed that thermal consolidation tests produced responses quantitatively comparable to those obtained under mechanical loading. This similarity points to a thermo-elastoplastic soil response, in which thermal effects contribute to hardening in a manner analogous to mechanical consolidation [23]. Analyses of coupled heat–deformation–flow processes in clayey soils, grounded in thermoporoelasticity concepts, have shown that the development of thermal stresses is closely associated with pore fluid expulsion. These coupling effects become particularly pronounced in materials characterized by high porosity and low permeability, where fluid migration is strongly constrained [24]. These observations underline the need for a sound understanding of thermomechanical soil behavior when modeling geomechanical problems involving thermal effects. This requirement becomes particularly critical for clayey soils, where thermal loading can substantially influence the mechanical response and, consequently, the reliability of numerical simulations.

In contact problems, the analysis must account for the complex interplay between mechanical and thermal fields. This includes heat transfer across actual contact areas, frictional heating, and the variation of material properties with temperature, all of which can significantly affect the overall mechanical response [25]. Such coupling may lead to instabilities in static thermoelastic contact, especially under conditions involving high heat flux, where localized thermal effects can significantly alter contact stresses and potentially compromise system stability (Gitterle, M., 2012). To tackle these complexities, advanced computational approaches – such as the finite element method incorporating mortar discretization and dual Lagrange multipliers – have been developed to accurately model and simulate these challenging contact problems [26]. These methods allow for the simultaneous modeling of wear phenomena and thermal coupling, either through internal state variables or using Arbitrary Lagrangian–Eulerian formulations. Moreover, adaptive computational strategies have been developed to address thermomechanically coupled multibody contact problems. By employing a posteriori error estimators grounded in projection techniques, these approaches manage spatial discretization and adaptively control time stepping, ensuring numerical stability and accuracy while capturing the intricate interactions between thermal and mechanical fields [27]. Such advanced approaches improve the fidelity of simulations, allowing for more reliable predictions of complex thermomechanical contact phenomena across a wide range of engineering applications. By capturing the coupled effects of heat transfer and mechanical interactions, these methods provide insights that are critical for the design and analysis of thermally loaded systems.

To solve a thermomechanical problem using the finite element method while accounting for contact phenomena, a structured approach is required. First, the thermal and mechanical equilibrium equations must be expressed in their variational forms, ensuring that the fundamental governing principles are faithfully represented in the numerical model. Second, contact conditions are incorporated by modeling contact forces as external constraints, with the penalty method applied in this study to enforce them reliably while maintaining numerical stability. Finally, the thermal and mechanical problems are coupled, explicitly capturing thermomechanical interactions and contact effects, so that the mutual influence between temperature variations and mechanical response is accurately represented, enabling realistic simulation of complex coupled phenomena.

***Variational formulation of the thermomechanical problem.*** *Thermal variational formulation*. The heat equation in materials is a partial differential equation

that describes the temporal diffusion of heat within a material. The following formula gives it

$$\frac{\partial T}{\partial t} - \alpha \nabla^2 T = 0,$$

where $\alpha = \frac{k}{\rho c}$ is the thermal diffusivity, with $T$ being the temperature; $k$ represents thermal conductivity, $\rho$ denotes density, while $c$ signifies specific heat capacity.

Multiply the heat equation by a test function $\upsilon$ and integrate by parts to obtain the weak form. This leads to

$$\int_{\Omega} \left( \frac{\partial T}{\partial t} \upsilon + \alpha \nabla T . \nabla \upsilon \right) d\Omega = 0.$$

This can be expressed in terms of mass and conductivity matrices as

$$M \frac{dT}{dt} + K_T T = 0.$$

$M$ represents the thermal mass matrix; $K_T$ denotes the thermal conductivity matrix; $T$ signifies the vector of nodal temperatures.

*Mechanical variational formulation*. The mechanical equilibrium is given by

$$\sigma = D\varepsilon,$$

where $\sigma$ represents the stress vector; $D$ denotes the stiffness matrix, and $\varepsilon$ signifies the strain vector. In its basic form, we express the equilibrium equation as follows

$$K_u u = F,$$

where $K_u$ represents the mechanical stiffness matrix, $u$ denotes the displacement vector; $F$ signifies the applied force vector.

Multiplying the equilibrium equation by a test function $\upsilon$, we obtain

$$\int_{\Omega} \sigma : \varepsilon(\upsilon) d\Omega = \int_{\Omega} F . \upsilon d\Omega.$$

This can be rewritten in its discrete form as

$$K_u u = F.$$

***Variational formulation of contact with penalty method.*** In a contact problem, we must enforce the non-penetration condition on the contacting surfaces. The penalty method is used to handle this condition.

Let $\mathbf{u}_1$ and $\mathbf{u}_2$ be the displacements of bodies 1 and 2, respectively, at a contact point. The non-penetration condition can be formulated as

$$g(\mathbf{u}_1, \mathbf{u}_2) \geq 0.$$

This means that the two bodies must not penetrate each other. If the bodies overlap $g(\mathbf{u}_1, \mathbf{u}_2) < 0$, a penalty is applied to prevent penetration.

The penalty method involves introducing a contact term that penalizes penetration. This term is based on a contact force that is proportional to the amount of overlap between the bodies.

The penalized contact force is

$$F_{contact} = \lambda g(\mathbf{u}_1, \mathbf{u}_2),$$

where $\lambda$ is the penalty factor and $g(\mathbf{u}_1, \mathbf{u}_2)$ is the separation distance between the bodies. If this distance is negative (i.e., the bodies overlap), the contact force $F_{contact}$ becomes positive, penalizing the penetration.

The contribution of contact in the variational formulation is introduced as a virtual contact force. The penalty term $\lambda g(\mathbf{u}_1, \mathbf{u}_2)$ is added to the mechanical formulation. This modifies the stiffness matrix and the force vector as follows

$$K_u u + K_{contact} u = F.$$

The contact matrix $K_{contact}$ depends on the geometry of the contact and the penalty factor $\lambda$.

***Coupled thermomechanical formulation with finite elements.*** Within the finite element framework, thermomechanical coupling can be addressed either through a monolithic approach, in which the thermal and mechanical problems are solved simultaneously, or via a partitioned approach, where the two problems are treated in an alternating manner. The coupling arises not only from the temperature dependence of material properties but also from heat transfer across the contact interface, ensuring that the mutual interactions between thermal and mechanical fields are fully represented and that the model captures the nuanced effects of contact conditions on the overall system response.

1. *Thermal*: The temperature $T$ influences mechanical parameters (such as Young's modulus, $E(T)$, thermal conductivity, etc.), indicating that the matrices $K_u$ and $K_T$ may vary throughout the solution process.
2. *Mechanical*: Displacements $u$ modify the geometry of the contact surfaces, thus affecting $g(\mathbf{u}_1, \mathbf{u}_2)$ and the contact force $F_{contact}$.

We solve the coupled system simultaneously. The coupled formulation becomes

$$\begin{bmatrix} M & 0 \\ 0 & K_u \end{bmatrix} \begin{bmatrix} \dot{T} \\ u \end{bmatrix} + \begin{bmatrix} K_T & 0 \\ K_{contact} & K_u \end{bmatrix} \begin{bmatrix} T \\ u \end{bmatrix} = \begin{bmatrix} 0 \\ F \end{bmatrix}.$$

***Procedures and modeling steps.*** The two-dimensional model shown in Fig. 1 was studied using ABAQUS software. This model represents a rectangular concrete footing, with a width of $B = 2$ m and a height equal to $h = B/8$. The footing rests on a clay layer that extends to a width of 20 times the footing's width (20 B) and has a height equivalent to six times the footing's width (6 B). This model aims to simulate the interaction between the concrete footing and the underlying clay layer, with the goal of better understanding the mechanical behavior of the entire system under load.

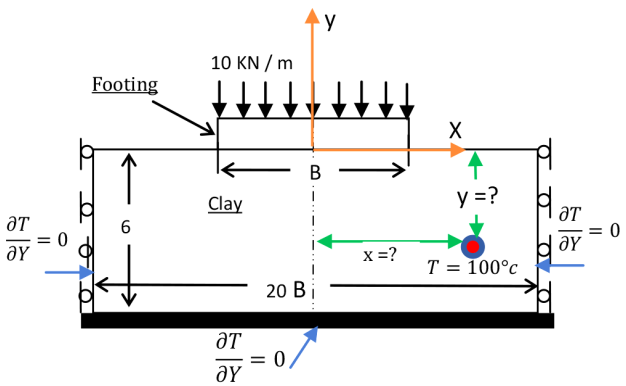


*Fig. 1. Geometric characteristics and boundary conditions*

The mechanical behavior of the studied clay is modeled according to a perfectly plastic elastic law. The criterion used to describe the transition between elastic and plastic behavior is the Mohr-Coulomb criterion; this is frequently utilized in the investigation of soil and cohesive materials.

The values of the essential parameters ( ρ, *E*, ν, *C*, φ, ψ) mentioned in Table, are especially derived from experimental testing conducted on clay samples obtained from the Erg Ferradj region in the Béchar province of Algeria. These experimental parameters reflect the geotechnical characteristics specific to this type of clay, which can vary considerably depending on local conditions such as mineral composition, moisture content, and the region's geological history. The obtained data are crucial for accurately modeling the behavior of this soil in engineering contexts, especially for foundation stability studies and civil engineering structures.

The material constituting the foundation is presumed to demonstrate linear isotropic elasticity, which implies that it reacts uniformly under the applied loads, regardless of direction. This premise is predicated on the notion that the foundation, due to its significantly higher stiffness compared to the surrounding soil, can be modeled as a rigid body. Indeed, this difference in stiffness allows for neglecting the deformations of the foundation compared to those of the soil, thus simplifying the analysis of its mechanical behavior. This approximation is particularly useful in geotechnical studies and structural stability calculations, as it enables the examination of the soil's response without the complexity of modeling the foundation's deformation.

To model the interaction, Coulomb's friction law was used, with a friction coefficient of 0.3, to describe the constitutive behavior of the contact. We chose the penalty method to treat the contact and friction, unless otherwise specified. The applied loading consists of a uniform load with an intensity of 10 kN/m$^2$. The system was fully discretized using quadratic 8-node isoparametric finite elements (Q8), with a soil density of 2,250 and 60 elements for the footing (Fig. 2). Furthermore, the presence of a heat source was considered, with a chosen temperature of 100 °C, located at a specific point under the footing, representing a Dirichlet boundary condition (imposed temperature) and the initial soil temperature is 20 °C degrees. The impact of temperature variation on the soil-foundation interface response was

*Table*

Constituent parameters of materials

| Settings | name | Clay | Concrete | Unity |
|---|---|---|---|---|
| Typical model | Model | MC | Elastic | – |
| Density | ρ | 1,700 | 2,200 | kg/m$^3$ |
| Young's modulus | *E* | $26 \cdot 10^5$ | $200 \cdot 10^8$ | N/m$^2$ |
| Poisson coefficient | υ | 0.3 | 0.23 | – |
| Cohesion | *C* | $5 \cdot 10^4$ | – | N/ m$^2$ |
| Friction angle | φ | 24.73 | – | ° |
| Friction coefficient | μ | 0.3 | – | – |
| Angle of dilatation | ψ | 10 | – | ° |
| Expansion | α | 0.0002 | $1.2 \cdot 10^{-5}$ | K$^{-1}$ |
| Thermal conduction coefficient | λ | 0.5 | 2.2 | W/m · K |

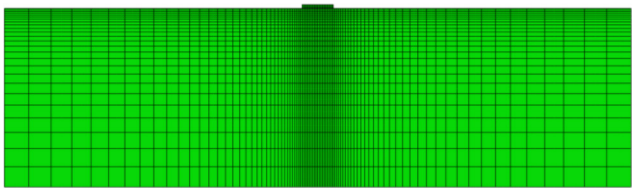

*Fig. 2. Mesh density*

analyzed by modifying the *x* and *y* distances of the heat source from the center of soil-footing interface, Fig. 1.

**Results and discussion.**

***For x constant (x = 0) and y variable (y = –4 m).***

From the graphs showing the evolution of normal contact stresses in Fig. 3, it is clearly noticeable that there is an increase in the normal stresses at the center of the interface footing-soil, as well as at the edges. Additionally, we can observe that this increase is significant in the central third for *y* = 0.4 m, which gradually decreases as they move away from the center, eventually becoming zero at the third of the foundation's edges. This implies that the contact area is reduced by approximately one third.

Conversely, there is an increase in the tangential stresses (Fig. 4), especially at the edges of the footing. Such a change in stress distribution is equivalent to a change in the mechanical properties of the soil, as understood by geotechnical engineers. Similarly to the tangential stresses, where they began to increase from zero until reaching their maximum in the central third, then began to decrease, eventually becoming negligible at the two-thirds mark of the edges. The summary of the results derived from the two previous Figures indicates that the closer the heat source is to the interface, the more significant its effect on the stresses.

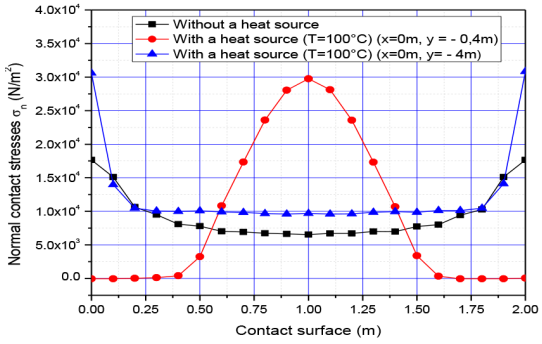


*Fig. 3. Evolution of the normal contact stresses (y = –4 m and y = –0.4 m for x = 0)*

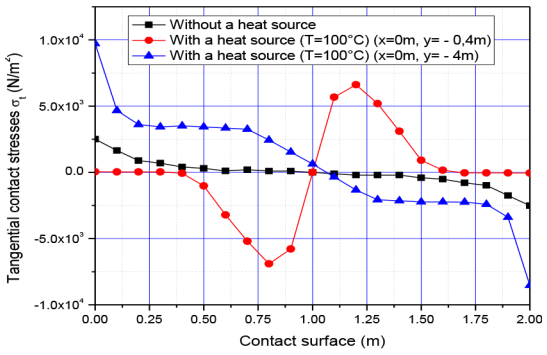


*Fig. 4. Evolution of the tangential contact stresses (y = –4 m and y = –0.4 m for x = 0)*

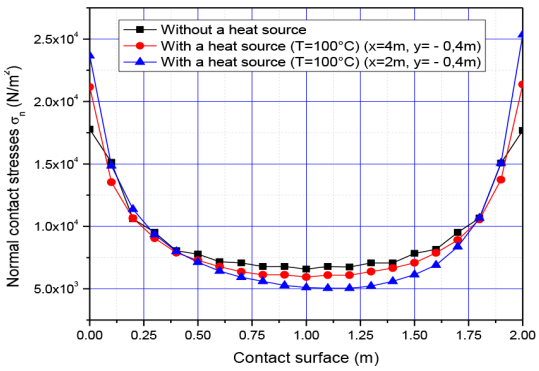


*Fig. 5. Evolution of the normal contact stresses (x = 4 m, x = 2 m for y = –0.4 m)*

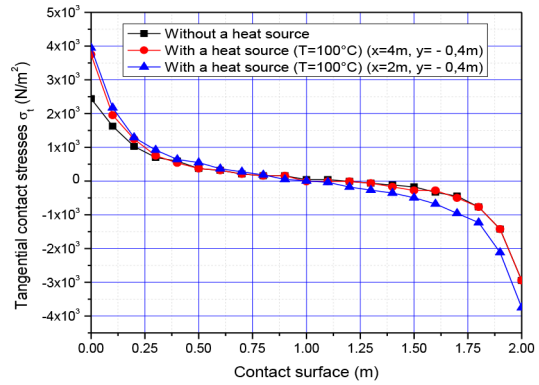


*Fig. 6. Evolution of the tangential contact stresses (x = 4 m, x = 2 m for y = –0.4 m)*

***For y constant (y = –0.4 m) and x variable (x = 2 m, x = 4 m).***

Figs. (5–6) show a slight change in the stress distribution. This change becomes more visible and significant, especially on the side of the source, as it gets closer.

In addition to the aforementioned points, an important observation drawn from these graphs is that the temperature completely alters the mechanical behavior of the foundation, transitioning from a centered footing to an eccentric one (which is akin to creating a moment).

**Conclusion.** Through this numerical study, we set about doing a thermomechanical coupling and showing the impact of a thermal field on the soil-sole interface. The developed model makes it possible to take into account the material and geometrical non-linearities, as well as those of contact.

The results indicate that the behavior of the soil-foundation interface is significantly influenced by the presence of a thermal field, which affects both the interface behavior and the distribution of stresses. So, one is obliged to take into consideration the thermal effect for the calculation of the soil-sole interaction especially if the latter is eccentric.

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## Вплив температурних коливань на межу розподілу «ґрунт-фундамент»

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**Мета.** Метою дослідження було вивчення реакції по лінії взаємодії «ґрунт-фундамент» на коливання температури. У цьому дослідженні аналізується вплив коливань температури на розподіл напружень на межі розділу «фундамент-ґрунт», що має вирішальне значення за наявності джерела тепла або в регіонах зі значними коливаннями температури.

**Методика.** Для моделювання взаємодії між пружнопластичним ґрунтом (за критерієм Мора-Кулона) й жорстким залізобетонним фундаментом із пружною поведінкою застосовується закон контакту й тертя із використанням методу контактних коефіцієнтів у межах методу скінченних елементів. Для аналізу впливу температури на сумісну роботу ґрунту й фундаменту враховується термомеханічна взаємодія, що дозволяє детально дослідити поведінку системи за різних умов.

**Результати.** Результати свідчать про те, що зміни температури ґрунту мають суттєвий вплив на розподіл контактних напружень на межі взаємодії «фундамент-ґрунт». Такі коливання можуть впливати на загальні експлуатаційні характеристики та стійкість фундаментів, особливо в умовах, коли температурні коливання є значними.

**Наукова новизна.** У цій роботі, разом із моделюванням усіх видів нелінійності (геометричної, матеріальної й контактної) методом скінченних елементів, представлено метод термомеханічного взаємозв'язку, що дає змогу точно проаналізувати вплив температури на взаємодію ґрунту й фундаменту – аспект, який часто ігнорується у традиційних дослідженнях.

**Практична значимість.** Отримані результати є цінними для інженерів, які займаються проєктуванням фундаментів, особливо в регіонах, де спостерігаються значні коливання температури, спричинені як природними явищами (наприклад, геотермальними гарячими водами), так і промисловою діяльністю (наприклад, підземними печами для обробки матеріалів), зокрема на об'єктах енергетики. Ураховуючи теплові ефекти при проєктуванні фундаментів, можна зменшити ризики, пов'язані із температурними змінами ґрунту й фундаментів, тим самим підвищивши стабільність і довговічність інфраструктури.

**Ключові слова:** *взаємодія «фундамент-ґрунт», тертя, зміна температури, термомеханічна взаємодія*