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A New Simplified Prediction Method of the Contact State between Shallow Foundations and Swelling Ground

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Abstract

Prediction of the contact state between soil and structure is a key step in any study of shallow foundations resting on swelling soil. However, in practice, the foundation designer has no simple and rapid method, at the design stage, to define the contact conditions. This study presents a new method, both simple and reliable, to predict the contact state. To do this, a soil-structure interaction model is developed. The building behavior is investigated with the Euler–Bernoulli beam theory and the ground behavior is investigated with a Winkler model. The soil-structure interaction is then, studied at the equilibrium state. The thereby obtained equation is analyzed and all of its parameters are synthesized in a new factor named "Detachment Factor". The decidability of the contact is thus reduced to the study of this single element, which allows a reasonable approach to the knowledge of the surface rate engaged in the shallow footings - expansive soil interactions. The conclusions of the current study are validated against five cases treated in the literature in various regions around the world. In addition, a parametric study of the "Detachment Factor" shows that each of its parameters (i.e. swelling stiffness, shape of initial soil surface, permissible deflection, structure geometry and loads) has a variable effect on the contact state between a footing and swelling ground. But, the structure load has the most significant effect on it.

Keywords: Shallow Foundation; Expansive Soil; Contact; Swelling Ground; Lift-off.

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1. Introduction

Nowadays, economic constraints enhanced by the scarcity of constructible land, lead to the execution of foundations sometimes in difficult geotechnical environment such as expansive soils. Expansive soils are known to swell on wetting and shrink on drying. Soils with high smectite (clay mineral) content exhibit maximum shrink-swell characteristics; however, any soil generally classified as clay will exhibit some shrink-swell characteristics [1].

Widespread all around the world, this natural risk of shrinkage-swelling of clay soils, although not dangerous for humans, causes each year considerable and often irreversible damage to several structures built without precautions on these soils, which triggers substantial financial losses for the countries concerned [2]. In order to understand the behavior of both structures and expansive soils, numerous in situ surveys were carried out in these countries [2-4]. It revealed that lightly loaded structures, especially individual masonry houses with shallow foundations built on expansive soil, are the most vulnerable to the shrinkage-swelling phenomenon and that a structural damage to

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buildings has been caused mainly by the differential heave of the foundation subsoils. It showed also that differential heave of the foundation subsoils depends upon a number of variables, such as lateral thickness of the clay substratum, non-uniformity of the soil, variations in water content beneath the structure, and other parameters related to the use and occupation of the particular building. Accurate comprehension of the behavior of a swelling soils and the interaction between the structure and the soil movement undergoing during a wetting or drying period is therefore fundamental for the design of shallow foundations on clayey soils.

Commonly used methods for the design of shallow foundations relying on expansive soil [5-7] shows that the prediction methods of soil swelling (shrinkage) have been continuously improved in particular with the understanding of the behavior of unsaturated soils. Those methods can be gathered into four (4) main categories: oedometer methods [8-10], soil suction methods [11-13], empirical estimating methods for soil deformation summarized by Nelson and Miller [14] and, finally, the hydro mechanical coupling methods [15-17]. Once the soil's susceptibility to swelling is determined, the deformation of the building on this deformed ground is then studied numerically by using finite element modeling software or analytically by applying the Winkler-type local strain model (1867), solved using Krylov functions. The latter approach has proved to be more appropriate for usual and standard designs than numerical resolution even though both methods are comparable in term of reliability. In practice, in order to match as closely as possible with reality, the engineer must define one of the major input value needed to perform a reliable modelization of the soil-structure system: the conditions of contact between clayey ground and foundation. In other words, it must be predicted if the contact between the soil and the structure will be either partial or total. However, there is no objective method to predict the state of swelling soil - structure contact. Indeed, the research carried out to date does not all agree on the same conclusions concerning the type of ground/structure contact and the criteria that define it. In their calculations, the researchers assume that the expansive ground/foundation contact is a priori partial. Although based on feedback from real experience, this choice is arbitrary and hence are restricted to the geographical location for which they are derived. In response to this issue, a new method is developed in this article. It defines, in a practical and precise way, the state of soil - structure contact and its extent by introducing a new parameter named "*the Detachment Factor*": it is an estimator of the contact area, both simple and convenient.

The current study starts by analyzing the response of the building-ground system in terms of building deflection induced by soil swelling (shrinkage) during a wet (drying) period, taking into account the phenomenon of clayey soil-structure interaction. To achieve this objective, the footing - clayey ground system is modelized at the equilibrium. The building's mechanical behavior is investigated with the Euler – Bernoulli beam theory, and the ground behavior is investigated with a Winkler model. As a result of this modelization, a parametric equation is proposed. An analysis of all parameters involved in this equation is held. It shows that they can be synthesized in a unique factor called "*Detachment Factor*". The conclusions of this approach are validated against five cases treated in the literature with several kinds of structures, in various regions around the world. The results of this study show a total agreement between the contact states predicted by the current study and the ones retained by authors in the literature.

In addition, a parametric analysis of all variables comprised in the formula of the "Detachment Factor" (i.e. swelling stiffness, shape of initial soil surface, permissible deflection, structure geometry and loads) is developed in this article. An answer is also given to the following question: is the state of soil - structure contact related to the soil or to the structure or is it the result of a swelling soil-structure interaction?

2. Materials and Methods

In the current analysis, the behavior of the expansive soil-structure system is modeled using the concept of beam on swelling dome proposed by Lytton (1977) study, because of its convenience and its ability to provide results with a level of precision comparable to the most sophisticated analyses (finite elements) [18]. In order to take into account the worst-case scenario, the foundation seating depth is taken equal to zero in this model. The most frequent situations of shallow foundations on swelling soils will be examined in this work, namely the swelling of the soil near the ends of the strip (edge heave) and the swelling of the soil under the center of the foundation (central heave).

The principles of the resistance of materials are used to calculate the foundation. The equations for this problem are based on the balance of forces involved; principle of action and reaction. The study of soil behavior is carried out using the techniques of soil mechanics. For the iterative calculation of the parameters "*C*" and "*a*" of the model presented below, an algorithm has been developed, using the Python language. The graphical representations are obtained using autoCAD and Excel software.

2.1. Clayey Ground Model

The soil can be modelled by elastic parameters such as Youngs Modulos and Poissons Ratio. The simplest model, however, is the Winkler spring in terms of a constant spring stiffness (k), named modulus of reaction. As it has been demonstrated by the analysis of Poulos (1984) study that the precise form of the soil model has relatively little influence on the strip behavior [19]. The behavior of the swelling clays is modeled by considering a homogeneous elastic expansive soil, so that the swelling of the soil is supposed to be uniform in the vertical direction (considering a single-layer model). The modulus of reaction, noted k, is assumed to be constant on the soil/footing contact area

2.2. Building Model

The geometry of the structure can be reduced into rectangular dimensions of length (L). For complex shapes, the plan of the structure can be divided into overlapping rectangles. So that in the present study, the building is modeled by an element of concrete beam of length L with fixed section, constant rigidity and tolerating a maximum admissible deflection Δ.

2.3. Load Model

In this model, the foundation beam is subjected to external loads, due on the one hand to the structure and on the other hand to the reaction of the swelling soil.

2.3.1. Superstructure Loads

A variety of structural loading patterns will occur in practice. However, this complexity can be reduced by simplifying the superstructure loads into a linear perimeter distribution W (kN/m) (wall loads), a linear distribution acting in the center of the building (partitions) P (kN/m) and a uniform distribution w (kPa). The representation of superstructure loads proposed in this work is considered, by Building Research Advisory Board (BRAB) (1968) [20], Mitchell (1984) [21], and Pidgeon (1980) [22] studies, as a more realistic model and allowing more conservative bending moments than if uniform distributions of the superstructure load have been adopted.

2.3.2. Reaction of the Support Soil Induced by the Expansive Soil-structure Interaction

The approach followed in this analysis for the calculation of the soil’s swelling reaction induced by the soil-structure interaction is as follows: at first, the clay soil surface’s free deformation as well as the deformation of the foundation are determined and then Winkler's model is used to find the equilibrium solution. Attention here will be focused on the simplification of the expression of the contact pressure between soil and the strip, by proposing a linear identification for the soil reaction under the frame Pi (kPa) using the method of least squares.

As proposed by Winkler (1867), the expression of the swelling soil reaction Pi, induced by the interaction between the swelling soil (modeled by springs) and the structure, is declined as follows:

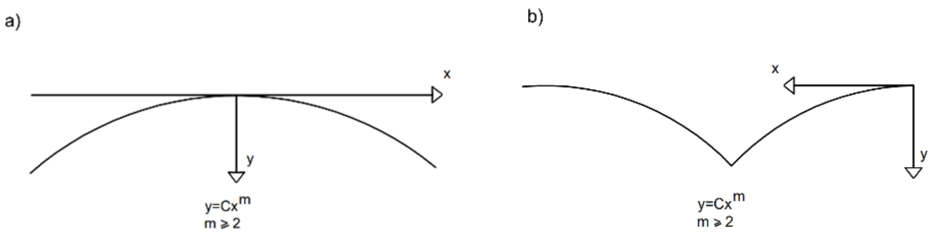
$$Pi = k\,(y - f) \tag{1}$$

Several procedures have been recommended for the determination of the soil reaction modulus k (kPa/m) (the Vesic triaxial test (1961) [23], the Terzaghi plaque test (1955) [24] studies …). In the current study, the following expression of the soil reaction modulus k (KPa) determined from the swelling tests is retained because of its adequacy with the Winkler model chosen above.

$$k = \frac{\sigma_a}{y_0 - y_a} \tag{2}$$

Where; σ_a is the pressure applied to the test specimen, y_0 is the amplitude of the free swelling of the soil and y_a is the amplitude of the swelling of the soil under the applied pressure σ_a.

Prediction of the distribution of “free-field” soil movement (under zero contact pressure) along the footing, due to swelling or shrinking is difficult, as the presence of the footing will influence this movement. In this model, the free deformation of the soil, called “swelling domes”, is represented by convex curves for the central heave and concave for the edge heave (Figures 1). This simplified approach involving the concept of a free-field soil “mound” is generally used for practical purposes.



Figures 1. Initially distorted soil surface: a) central-heave; b) edge-heave [18]

For the maximum soil swell of Y, the shapes in Figure 1 (a) and (b), can be approximated by the Lytton equation, (Lytton 1977) [18] study, as follows:

$$y(x) = (\frac{2x}{L})^m Y \tag{3}$$

With y denotes the displacement of the ground measured from the high point (m),Y the Maximum soil swell (m), x the horizontal distance from the high point and m (m≥2) the form factor (function of L and the depth of variation of the water content in the soil, the active zone).

The exponent "m" in Equation 3 has been found to have a major influence on the footing design, as noted by Mitchell (1984) [21] and Pidgeon (1980) [22] studies. The following expression for the form factor "m" (Equation 4), established by Mitchell (1984) study from analytical solutions of the steady state Diffusion Equation, is adopted in this study:

$$m = 1.5\frac{L}{a} \tag{4}$$

Where L is the length of the area covered and "a" is the depth of the area of variation in water content under the cover (active area).

- In this model, the profile of the foundation (Figure 2), as it interact with the soil, is approached by an equation similar in type to the one defining the soil movement.

Lift-off is defined in this article as being the point of the soil - foundation interface from which the deformations are different. C is *the detachment index* defined as the ratio between the soil - foundation contact length and the total length of the foundation ($0 \leq C \leq 1$).

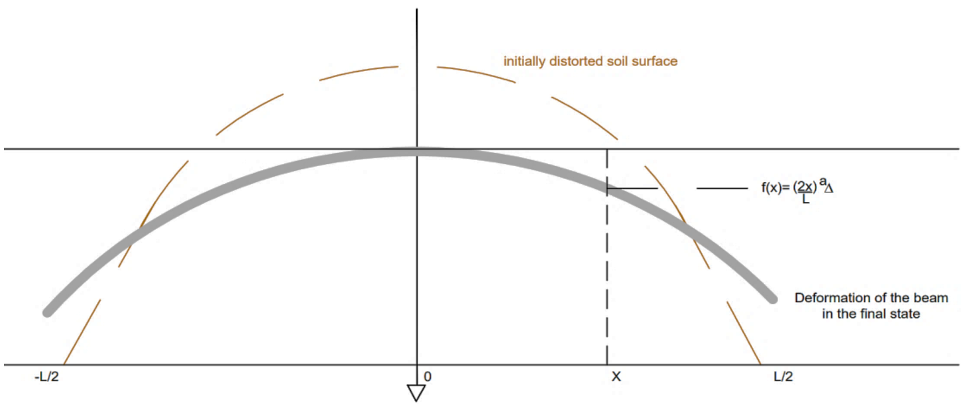


Figure 2. Deformation of the beam in the final state

Inspired by the models of Lytton (1977) [18] and Mitchell (1984) [21] studies the expression for beam deformation is declined as follows:

$$f(x) = (\frac{2x}{L})^a \Delta \tag{5}$$

In Equation 5, x $(-L/2 < x < L/2)$ is the horizontal distance of the section studied compared to the center of the beam, an exponent of this equation "a" is an integer and Δ is the allowable deflection of the structure.

− For the modeling of the studied system, a linear representation is chosen for the soil reaction under the frame Pi (KPa) by using the method of least squares:

$$Pi(x) = Pi\,max\,(\frac{-2}{CL}x + 1)$$

With $Pi\,max = k((C)^m Y - (C)^a \Delta)$ (6)

Where $Pi\,max$ denotes the maximum value of the contact pressure of the swelling soil (wettest zone).

From the point where lift-off occurs, the two edges along which there has been loss of contact behave like a console beam and the ground reaction is suppressed. Figure 3, summarizes the method explained above for obtaining the expression of the swelling soil reaction Pi.

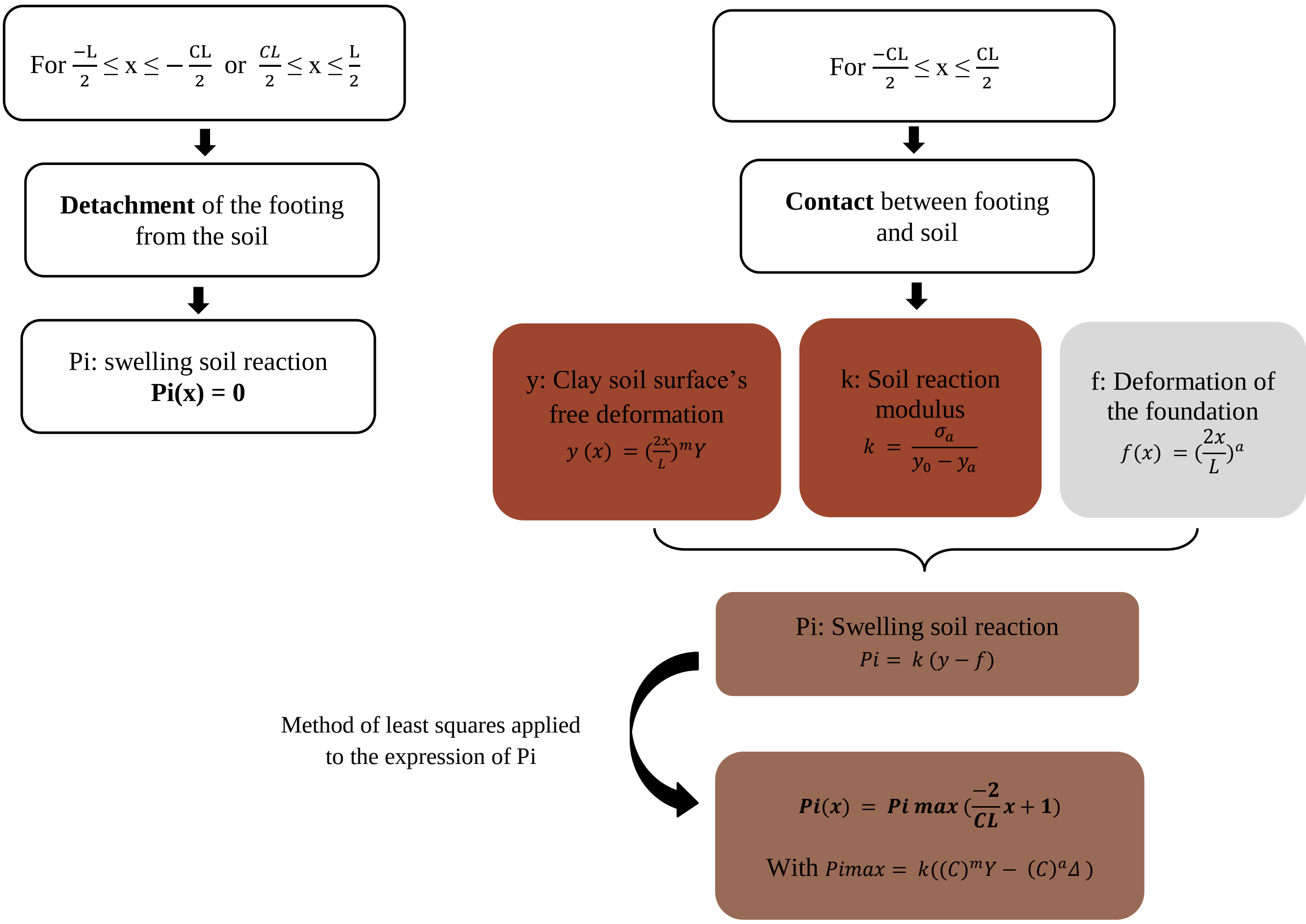
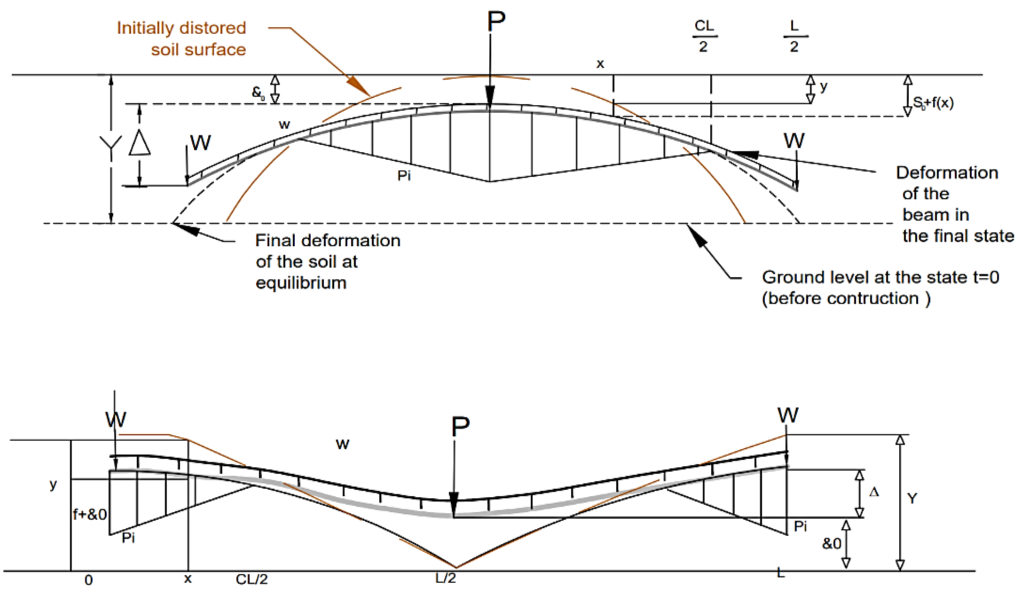


Figure 3. Proposed method for obtaining the expression of the swelling soil reaction Pi

2.4. Representation of Model Parameters

Figures 4 shows the model parameters and expected beam deflection after being subjected to swelling action at its center and extremities. In this figure, y(x) is the Free-field soil movement (assumed to occur in the absence of the footing) (m), f(x) is the deflection of the beam (m), which is considered negative when the shape is convex (according to beam theory convention), δ_0 is the settlement at point $x = 0$ and C *the detachment index*.

a)



b)

Figures 4. Calculation diagram of the strip on swelling ground a) Centre Heave (normal or dry season); b) Edge Heave (rainy season)

Due to the symmetry of the problem, the analysis will be limited to half the beam. Thus, the strip footing behaves like a console beam of maximum length L / 2 and embedded at its origin x = 0.

The boundary conditions resulting from this modelization are the following ones:

- $f(0) = f'(0) = 0$;
- Derivative of the deformation on the point of separation $(x = CL/2)$ gives the following two boundary conditions: $f(\frac{CL}{2})^- = f(\frac{CL}{2})^+$; $\frac{df}{dx}(\frac{CL}{2})^- = \frac{df}{dx}(\frac{CL}{2})^+$.
- $f(\frac{L}{2}) = \Delta$ et $y(\frac{L}{2}) = Y$.

2.5. Static Equilibrium of the Expansive Soil-beam System

Depending on the water infiltration conditions, the soil structure system evolves over time towards a state of equilibrium. Figure 5 shows a diagram of the soil-structure interaction scenario during a swelling of the ground, developed by analogy with the situation of soil shrinkage [2].

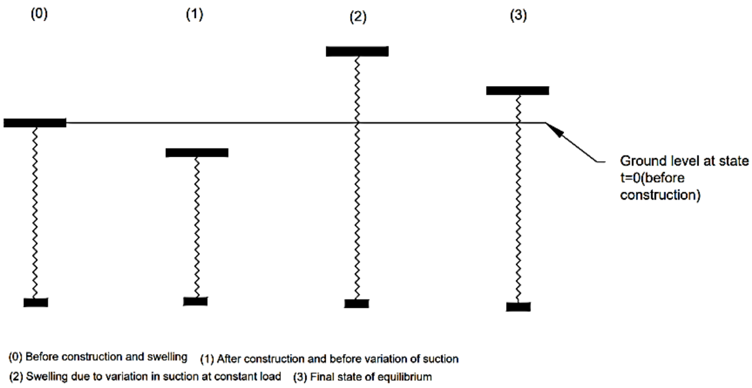


Figure 5. Scenario of the soil-structure interaction during swelling of the expansive soil under the construction

According to this calculation model, when this beam is in a state of final equilibrium, the internal forces at any point x of the beam (bending moment $M(x)$, shear force $V(x)$) and its deflection $f(x)$ can be determined using classical formulas for Materials Resistance calculation:

Under the condition of loss of contact between the soil and the strip over a certain length, 3 conditions must be verified:

- ✓ The superstructure loads must balance the soil pressure $(\boldsymbol{Pi})$ spread along the soil - beam contact surface.
- ✓ At any point x of the beam, the moments due to the external forces $M(x)$ (due on the one hand to the superstructure forces and on the other hand to the contact pressure of the swelling ground) must be equal to the internal moment of the strip:

$$M(x) = \frac{\mathrm{EI} \times \mathrm{df(x)}^2}{\mathrm{dx}^2} \tag{7}$$

The deformation of the beam can therefore be calculated by the general equation of the beam by integrating Equation 7 twice.

- ✓ The displacement of the strip f must be equal to the displacement y of the soil over the entire length of the soil foundation contact (CL).

Thus, the equation of balanced forces in the vertical direction can be written as follows:

$$\sum F = P + \frac{\mathrm{w \times L}}{2} + W = \frac{\mathrm{L \times k}}{4}\left((\mathrm{C})^{\mathrm{m+1}}\mathrm{Y} - (\mathrm{C})^{\mathrm{a+1}}\Delta\right) \tag{8}$$

If the ground remains in contact with the beam along its length therefore $C = 1$ and the preceding equation becomes:

$$P + \frac{w \times L}{2} + W = \frac{L \times k}{4}(Y - \Delta) \tag{9}$$

$Fd = \frac{Lk}{4}(Y - \Delta)$ will be defined as "*Detachment Factor*".

To decide whether there is full or partial contact, the following approach is suggested:

- If the total structural load $\sum F$ are less than the value of the "Detachment Factor" then lift-off occurs at $x = \frac{CL}{2}$.
- If not, no lift-off occurs and $C = 1$.

Figure 6, summarizes the method explained above for predicting the contact state between shallow foundation and swelling soils.

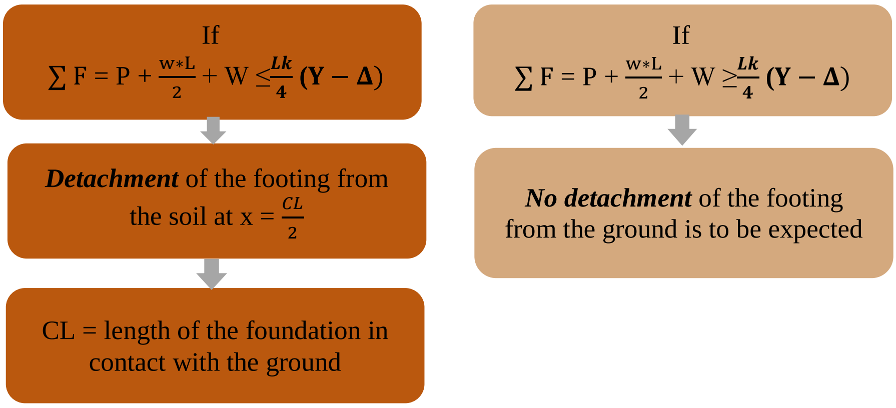


Figure 6. Flowchart of methodology used in the prediction of the contact state between shallow foundations and swelling soils

2.6. Values of Parameters "*C*" and "*a*":

For the determination of the values of parameters "*C*" and "*a*" of this model, an algorithm has been developed using the Python language. Indeed, an iterative procedure is carried out and it starts by attributing an initial value to the parameter "*a*", then the value of "*C*" is calculated by Equation 8. The values of the footing deformation $f(x)$ at two different points of the beam , obtained by using Equations 5 and 7, allow to check the assumed value of a from the Equation 10:

$$a = ln\left(\frac{f1(x1)}{f1(x2)}\right) / \, ln\left(\frac{x1}{x2}\right) \tag{10}$$

The correct value of a is then determined through a process of trial and error.

3. Results

The distribution of deflection along the beam for a specified distribution of "free-field" movements, deduced from this model, is re-presented by the following expressions:

- For $0 \leq x \leq \frac{CL}{2}$

$$f_1(x) = \frac{1}{EI}\left(\frac{Pimax}{60 \times CL}x^5 - \frac{(Pimax - w)}{24}x^4 + \left(\frac{(CL \times Pimax)}{24} - \frac{wL}{12} - \frac{W}{6}\right)x^3 + \left(\frac{wL^2}{16} + \frac{WL}{4} - \frac{(CL)^2 Pimax}{48}\right)x^2\right) \tag{11}$$

- Wile for $\frac{CL}{2} \leq x \leq \frac{L}{2}$

$$f_2(x) = \frac{1}{EI}\left(\frac{w}{24}x^4 - \left(\frac{wL}{12} + \frac{W}{6}\right)x^3 + \left(\frac{wL^2}{16} + \frac{WL}{4}\right)x^2 - \frac{(CL)^3 Pimax}{192}x - \frac{3 \times Pimax}{640}(CL)^4\right) \tag{12}$$

Where W (kN/m) is a linear perimeter distribution (wall loads), w (kPa) is a uniform distribution of superstructure loads and Pi max is the maximum value of the contact pressure of the swelling soil given by Equation 6. Furthermore, L (m) is a footing length and C is the detachment index, defined as the ratio between the soil - foundation contact length and the total length of the foundation ($0 \leq C \leq 1$). The value of the parameter C can be determined from the iterative procedure developed in section 2.6.

The prediction of the contact state between the shallow stiffened footing and the swelling (or shrinking) ground begins by calculating the "Detachment factor" by the following formula:

$$Fd = \frac{Lk}{4}(Y - \Delta) \tag{13}$$

Then, the value of the "detachment factor" will be compared to the value of the structural forces.

- If the total structural load $\sum F$ ($\sum F = P + \frac{w \times L}{2} + W$) are less than the value of the "Detachment Factor" $Fd = \frac{Lk}{4}(Y - \Delta)$then lift-off occurs at $= \frac{CL}{2}$.

The length of the foundation in contact with the soil can then be evaluated by CL.

- If not, no lift-off occurs and $C = 1$.

3.1. Influence of Design Parameters (Y, K, L, Δ and w) on the State of Soil- shallow Foundation Contact

A parametric study of the different components of the soil-structure contact state is presented below. Figures 7 to 10 show the influence of each of the parameters determining the "Detachment factor" for different values of superstructure loads ($\sum F$(kN/m) equivalent loads). Each time, the evolution of the "Detachment factor" Fd is examined by varying a single parameter while keeping the others constants.

It should be noted that:

The range of applied loading values w (kPa) considered in this work (varying between 30 KPa and 300 KPa) is limited to a realistic values corresponding to the buildings most affected by the shrinkage-swelling hazard identified in the literature (i.e. building collective housing, individual house, administrative building, etc.), in particular by Jahangir (2011) [2].

The interval variation of the four parameters value Y, k, L and Δ is retained taking into account the characteristics of different swelling clay soils and different types of construction discussed in the literature, among others in the studies of Mitchell (1984) [21], Ejjaaouani (2008) [1], and Jahangir (2011) [2, 15] studies.

Consequently, the values chosen have no character of generality and are only working hypothesis.

Soil Reaction Modulus k

Figure 7 shows the influence of the reaction modulus of the swelling soil k (kPa/m), combined with different loads $\sum F$ (kN/m), on the soil /shallow foundation contact state for L = 12 m, Δ = 12 mm, Y = 160 mm.

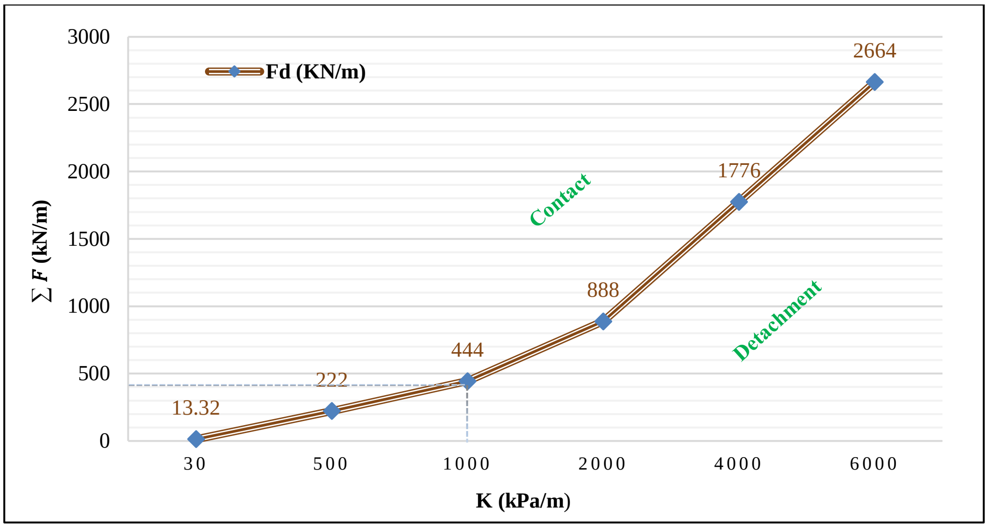


Figure 7. Effect of the reaction modulus of the swelling soil k (kPa/m) on the state of ground - shallow foundation contact

It is observed from Figure 7 that for soils characterized by a reaction modulus k less than 1000 kPa/m, the contact between the soil and the structure over the entire length of the foundation is to be expected for a value of $\sum F$ exceeding 444 kN/m (corresponding to the building load w=74 kPa). A value for which the detachment factor and the superstructure forces take the same value $Fd = \sum F$. Moreover, to balance the swelling pressure of the expansive soil having a reaction modulus k of 2000KPa/m and to avoid the partial detachment of the structure, it would be necessary to design a structure loaded with more than 150 kPa. For medium-weight buildings (w≤300 kPa corresponding to $\sum F$≤1800 kN/m) detachment can only occur in the case of a Clayey ground with a reaction modulus k exceeding 4054 kPa/m.

This abacus shows that the more the value of k increases and the load decreases, the more the state of soil-structure contact evolves towards partial separation. Furthermore, for a given value of k, the increase in the load of the structure leads to an extension of the soil-structure contact surface.

The value of k = 2000 kPa is used in the following analyzes. A value considered as representative of the swelling soils most encountered in Morocco.

Free Swelling of Soil Y

Figure 8 shows the influence of free swelling, combined with different loads w (kPa), on the contact state in this figure, L=12 m, Δ=12 mm and k=2000 kPa/m.

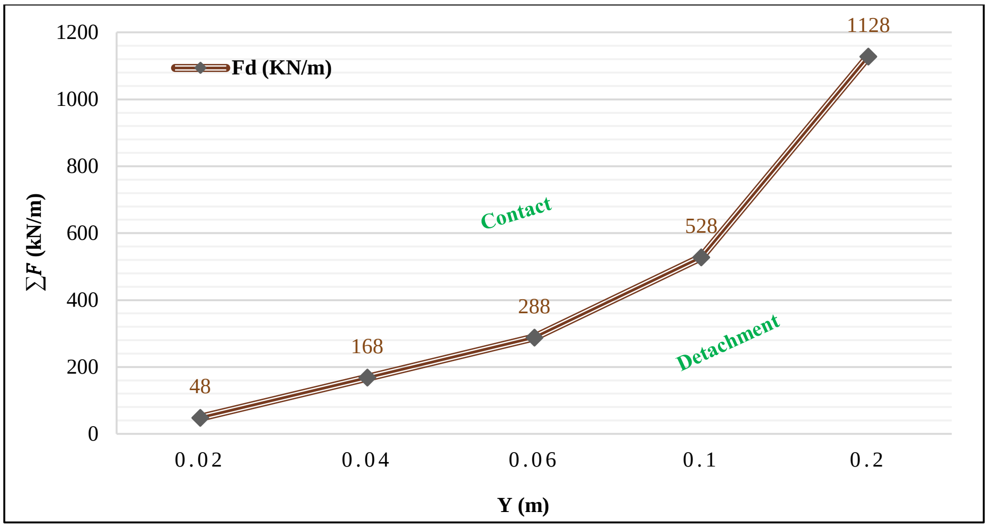


Figure 8. Effect of free swelling Y (m) on the state of ground / shallow foundation contact

Under these conditions, for light structures (corresponding to the building load w≤ 50 kPa) lift-off is to be expected for a clayey ground with a free swelling Y exceeding approximately 6 cm. Moreover, for a clayey soil characterized by a free swelling Y = 0.1 m the perfect contact is to be expected between structure and clayey ground loaded more than 88 kPa; a value for which Fd = $\sum F$=528 kN/m.

It is noted from the Figure 8 that for a fixed load w (kPa), when Y increases the contact state tends towards partial separation. However, when the external load exceeds 200 kPa (corresponding to $\sum F$ =1200 kN/m), a ground-footing contact is to be expected along the foundation (for the usual values of Y).

Permissible Deflection of the Structure Δ

Figure 9 illustrates the influence of the variation of the Permissible deflection of the beam Δ, combined with different loads w (kPa), for L = 12 m, Y = 16 mm, K = 2000 kPa/m.

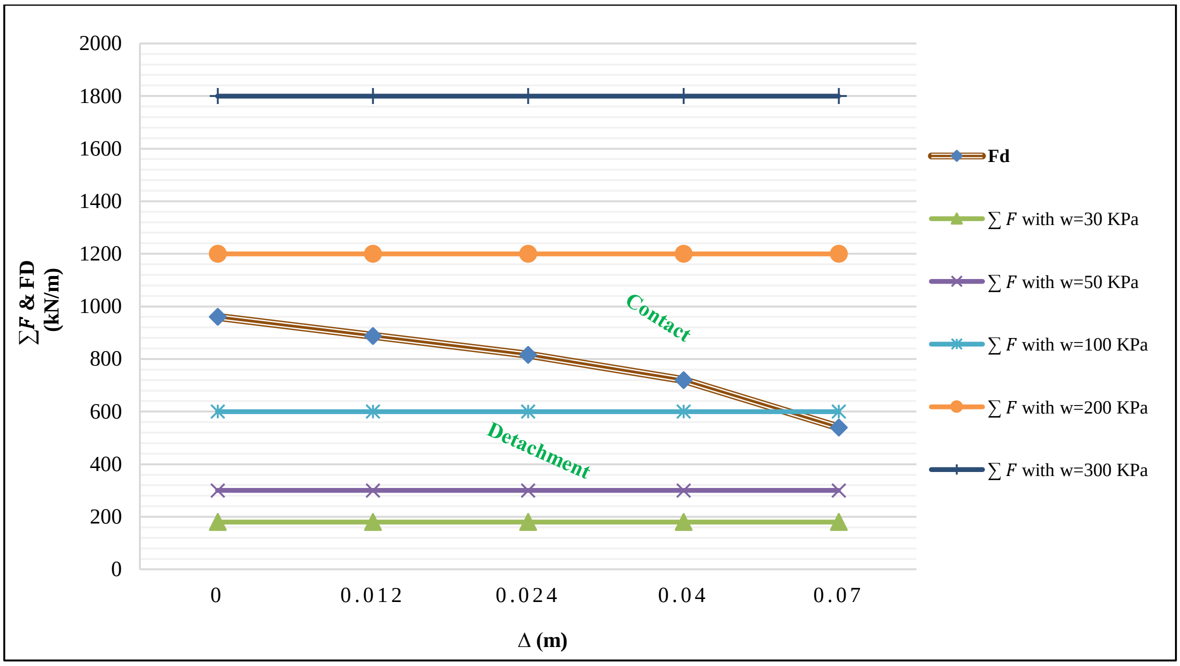


Figure 9. Effect of Permissible deflection of the structure Δ (m) on the state of ground / shallow foundation contact

This Fig. predicts, for the values of Δ used in this analysis, a loss of contact between a clayey ground and light constructions (w≤50 kPa). However, a perfect contact between the ground and the structure is to be expected for structures whose weight exceeds 100 kPa and Δ exceeds 6 cm.

This Fig. shows that for values of Δ less than 6 cm, the state of ground / shallow foundation contact is more sensitive to the importance of external loads than to the rigidity of the structure. According to the method presented above for loads exceeding 170 kPa, a ground - building contact is to be expected along the foundation regardless of the flexibility of the structure. When the foundation is flexible (Δ significant) it will tend to follow the deformation of the swelling soil and therefore keep contact with the soil over its entire length.

Foundation length L

The influence of the length of the foundation L, combined with different loads w (kPa) on the contact state, for Y=160 mm, K=2000 KPa/m at Δ=L/1000 is shown in Figure 10.

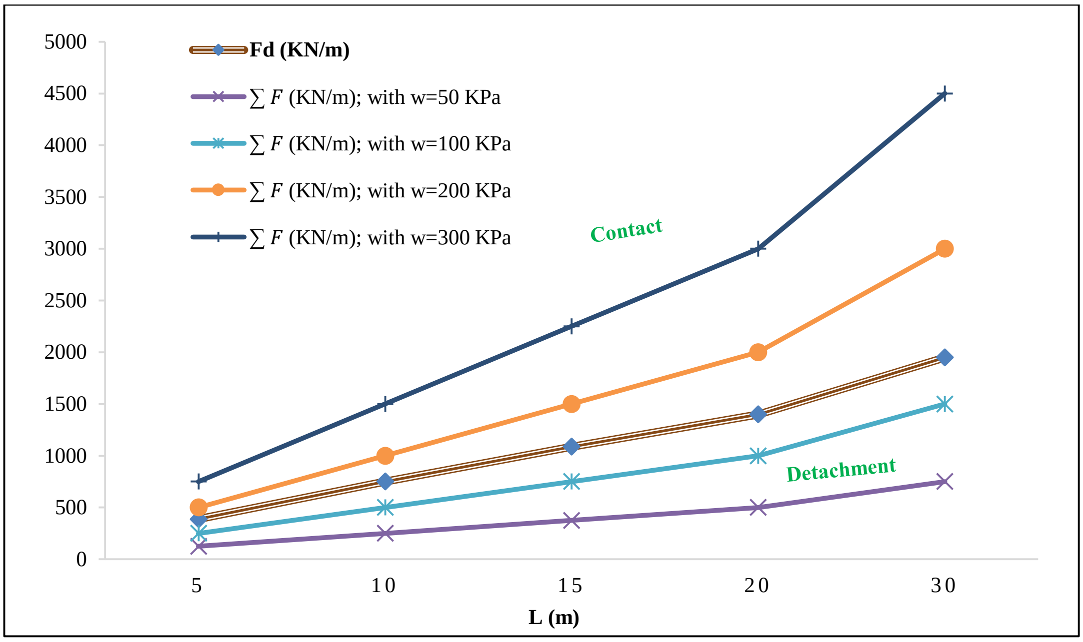


Figure 10. Effect of the length L (m) of the foundation on the state of ground / shallow foundation contact

Figure 10 illustrates the relatively small effect of L on the conditions of contact soil-structure. For the values of k, Y and Δ used in this example, the contact between a retained clayey soil and a structure that generate a load less than 100 kPa would always be partial regardless of the length L of this building. While a structure loaded with more than 200 kPa would be in contact over its entire length L with the supporting clayey soil, once again, regardless of the length of this building.

Furthermore, it can be deduced from Fig.10 that the increase in the load generates an increase in the extent of the soil-structure contact surface. Therefore, for a load exceeding 200 KPa no detachment of the footing from the ground is to be expected.

4. Discussion

Most of the studies consulted as part of this work assumed a partial detachment of the structure from the support soil. It turns out that these studies do not provide any justification for the choice of the soil-structure contact state. However, Ejjaaouani (2008) [1] explains that the soil-structure contact is always maintained because of the plastic behavior of the supporting clay soil which tends to eliminate the void between the soil and the structure during its humidification. Still, due to its general nature, this hypothesis also applies to clay soils studied in research where the detachment hypothesis has been adopted.

So, is the state of soil-structure contact related to the soil, to the structure, or to the interaction of the two? Common sense and intuition all lead to the hypothesis of reconciliation between the ground and the structure working in interaction.

None of the studies consulted as part of this work offers an objective method for predicting the state of swelling soil/structure contact. The new method developed above fills this void. It allows to define precisely the state of contact and its extent from a single factor named "Detachment Factor" Fd.

In addition, the expression of the factor $Fd = LK \times (Y - \Delta)/4$ provides a clear and tangible answer to the question raised above since it shows that the state of contact depends simultaneously on the characteristics of the soil and the structure. As confirming by the parametric study developed herein.

Validity of the Approach to Predicting the State of Soil / Structure Contact

In this section, the method proposed in this article for the prediction of the swelling soil-structure contact state is validated against several five cases treated in the literature, by Ejjaaouani (2008) [1], Mitchell (1984) [21], Viet Do et al. (2008) [25], and Baheddi (2007) [26] studies. In various regions around the world (Morocco, Australia, France…), treating several kinds of structures (wide variation in geometry, stiffness and loads) and several types of clayey soils (different swelling profiles and reaction modulus k).

To do this, the value of the "Detachment factor" Fd is first determined for each of the five cases studied by using the data from each of these studies. Then by applying the method of the current study, the prediction of the state of ground - footing contact becomes possible by simply comparing the value of Fd given by Equation 13 with the load of the building ΣF (with $\Sigma F = P + \frac{w*L}{2} + W$).

Table 1. Validity of the soil/structure contact state prediction approach

References	K (KPa/m)	L (m)	Y (m)	Δ (m)	w (KPa)	Fd	ΣFsup	Contact state Predicted by the current study	Contact state retained by the author	
Jaaouani (2008) [1]	2247.2	9	0.16	0.009 (*)	200	763.49	900	No lift-off	No lift-off	✓
Viet Do et al. (2008) [25]	30000	10	0.1	0.01 (*)	Not specified	6750	6750	Lift-off (**)	Lift-off	✓
Baheddi(2007) [26]	1104	6	0.09	0.006	15	139.10	45	Lift-off	Lift-off	✓
Mitchell (1984) [21]	1000	12	0.075	0.012	8,17	189	49,02	Lift-off	Lift-off	✓
Mitchell (1984) [21]	2500	14.05	0.02	0.007	7,27	114.16	51,07	Lift-off	Lift-off	✓

It should be noted that: (*)The expression $\Delta = \frac{L}{1000}$ is used in the current study if Δ was not specified by Jaaouani (2008) [1] and Viet Do et al. (2008) [25] studies. (**) For the case of Viet Do et al. [25] study the value of the charges due to the structure was not specified. A reverse calculation, adopting the method of this article, found that the minimum value of the external load required to avoid detachment in this example would be 1350 kPa. However, according to the bibliographical research as well as the various investigations carried out within the framework of this work, the types of works recommended or designed with shallow foundations on a clay mass represent loads much lower than this value (1350 kPa). This is the reason why a detachment is intended.

Table 1 notices a total agreement between the contact states predicted by the current study and the ones retained by Ejjaaouani (2008) [1], Mitchell (1984) [21], Viet Do et al. (2008) [25], and Baheddi (2007) [26] studies. Despite of the large variation of soils and structures treated.

- The parametric study developed previously, on the influence of design parameters (Y, K, L, w and Δ) on the state of soil-structure contact, reveals the following:

- The soil-structure contact conditions are very sensitive to the value of the swelling soil reaction modulus k, whether for small or large loads. This is why the determination of this parameter must be done with care.

- The free swelling of the soil is a determining factor in the prediction of the state of soil-structure contact, especially for low loads (w ≤ 200 KPa).

- As demonstrated in Figure 10, when the foundation is flexible (Δ large) it will tend to follow the deformation of the swelling soil and therefore keep contact with the soil over its entire length. While for a rigid building, a detachment can occur, since the displacement of the rigid body and the deformation of the building are limited because of the high rigidity of the building. Which is in accordance with the results of Jahangir (2011) [2] Figure 11.

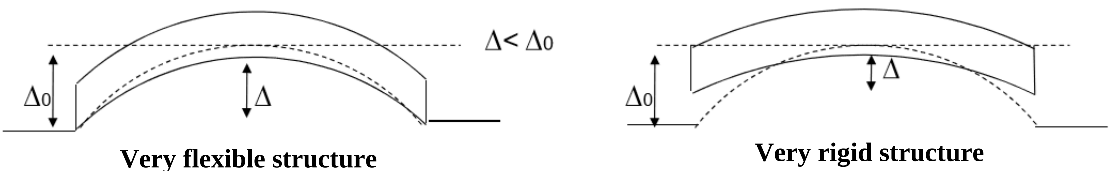


Figure 11. Settlement of soil and structure taking into account the soil-structure interaction [2]

- The effects of the length of the footing on the ground / footing contact state are found to be relatively small.

For the range of values of k, Y and Δ considered in this analysis, the increase in load generates an increase in the extent of the soil-structure contact surface. For a load exceeding 200KPa, no separation is to be expected. This is in agreement with the BRAB (Building Research Advisory Board) method of raft base design, study [20], which is based on the assumption that the support ratio C (determining the portion of the foundation area in contact with the ground) is independent of the length of the structure.

Finally, this parametric study clearly reveals the influence of the value of the construction loads on the state of contact between the soil and the structure. So that the increase in the load of the structure always tends to widen the footprint of soil-structure contact.

5. Conclusions

A new method for the prediction of the contact state between a shallow foundations and expansive soil is presented. It allows defining precisely the state of contact and its extent from a new single factor named *"Detachment Factor"* $Fd = LK \times (Y - \Delta)/4$. In order to reach this objective, a model of analysis is developed for the design of a shallow footing on expansive soil, for both center and edge heave. It is based on a simplification of the expression of soil pressure and is derived from an integration of the beam-on-Winkler mound equation. Then, by analyzing the response of this model at equilibrium, the decidability of the contact state (partial or total) amounts to comparing the value of Fd with the value of the structure loads ΣF.

A parametric study of the *"Detachment Factor"* has revealed that all the parameters of which it is composed have an impact on the state of soil-structure contact at varying levels. The length of the foundation being the least influencing one. The current study also allowed us to conclude that the state of soil / structure contact does not depend only on the characteristics of the soil or the structure but on a combination of both.

Results from the new method and those from Ejjaaouani (2008) [1], Mitchell (1984) [21], Viet Do et al. (2008) [25] and M. Baheddi (2007) [26] studies are compared and have shown the accuracy of the developed method.

The results and the discussion clearly show that the proposed method complies with the standards in use in the field of sizing footings on swelling ground. However, it would be valuable in the future to consider an extension of this technique to massifs with heterogeneous characteristics.

6. Declarations

6.1. Author Contributions

Conceptualization, Z.F., N.L., and J.B.B.; writing—original draft preparation, Z.F., N.L., and J.B.B.; writing—review and editing, Z.F., N.L., and J.B.B. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Ejjaaouani, Houssine. "Interactions of foundations and expansive soils: pathology, calculations and experimental studies." PhD Thesis Engineering Sciences [physics], Ecole des Ponts ParisTech, 2008.

[2] Jahangir, Emad. "Phénomènes d'interaction sol-structure vis-à-vis de l'aléa retrait-gonflement pour l'évaluation de la vulnérabilité des ouvrages." Ph.D. diss., Institut National Polytechnique de Lorraine-INPL, 2011.

[3] Snethen, D.R. "Three Case Studies of Damage to Structures Founded on Expansive Soils", Fifth International Conference on expansive Soils, Adelaide, South Australia, 218-221, (May 1984): 218-221.

[4] Wei, Xin, Chongyang Gao, and Ke Liu. "A Review of Cracking Behavior and Mechanism in Clayey Soils Related to Desiccation." Advances in Civil Engineering 2020 (August 14, 2020): 1–12. doi:10.1155/2020/8880873.

[5] Chen, F.H. "Foundations on expansive soils. Developments in Geotechnical Engineering. Elsevier Scientific Publishing Company", (1975).

[6] Karkush, Mahdi O, and Ala N. Aljorany. "Numerical Evaluation of Foundation of Digester Tank of Sewage Treatment Plant." Civil Engineering Journal 5, no. 5 (May 22, 2019): 996–1006. doi:10.28991/cej-2019-03091306.

[7] Mali, Shivanand, and Baleshwar Singh. “Behavior of Large Piled-Raft Foundation on Clay Soil.” Ocean Engineering 149 (February 2018): 205–216. doi:10.1016/j.oceaneng.2017.12.029.

[8] Abbas, H. O. “Laboratory Study on Reinforced Expansive Soil with Granular Pile Anchor.” International Journal of Engineering 33, no. 7 (July 2020). doi:10.5829/ije.2020.33.07a.01.

[9] LI, Kai, Liang Kong, Hossein Nowamooz, and Cyrille Chazallon. “The Mechanical Behavior of an Expansive Soil Due to Long-Term Seasonal Rainfalls.” Edited by R. Cardoso, C. Jommi, and E. Romero. E3S Web of Conferences 195 (2020): 02019. doi:10.1051/e3sconf/202019502019.

[10] Fredlund, D. G. “Prediction of ground movements in swelling clays”, 31st Annual Soil Mechanics and Found Engineering Conference. University of Minnesota, Minneapolis, (1983).

[11] Technical Manual. “Foundations in Expansive Soils”, Headquarters, Department of the Army. TM 5-818-7, (1983).

[12] R.G. McKeen. “A model for predicting expansive soil behavior", Proceedings of the 7th International Conference on Expansive Soils, Dallas, Texas, (1992):1-6.

[13] Ben Bouziane, J., R. Khalid, and M. Sahli. "Étude de la pression de gonflement de deux sols argileux compactés statiquement par rapport aux contraintes de compactage." Comptes rendus, 13ème Congrès Régional Africain de Mécanique des Sols et de Géotechnique, Marrakech (2003): 381-387.

[14] Nelson, J. D. and Miller, D.J. “Expansive Soils: Problems and Practice in Foundation and Pavement Engineering”.John Wiley & Sons, Inc., New York, NY, (1992).

[15] Jahangir, Emad, Olivier Deck, and Farimah Masrouri. “An Analytical Model of Soil–structure Interaction with Swelling Soils During Droughts.” Computers and Geotechnics 54 (October 2013): 16–32. doi:10.1016/j.compgeo.2013.05.009.

[16] Soltani, Deng, Taheri, Mirzababaei, and Vanapalli. “Swell–Shrink Behavior of Rubberized Expansive Clays during Alternate Wetting and Drying.” Minerals 9, no. 4 (April 9, 2019): 224. doi:10.3390/min9040224.

[17] Wray, W. K., B. M. El-Garhy, and A. A. Youssef. “Three-Dimensional Model for Moisture and Volume Changes Prediction in Expansive Soils.” Journal of Geotechnical and Geoenvironmental Engineering 131, no. 3 (March 2005): 311–324. doi:10.1061/(asce)1090-0241(2005)131:3(311).

[18] Lytton, R.L. “Foundations on expansive soils”, Numerical methods in geotechnical engineering, McGraw-Hill, New York, (1977).

[19] Poulos, H.G. “Parametric Solutions for Strip Footings in Swelling and Shrinking Soils”, Fifth International Conference on Expansive Soils, Adelaide, South Australia, (1984).

[20] BRAB. “Criteria for Selection and Design of Residential Slabs-on-Ground” Building Research Advisory Board, National Research Council, US National Academy of Sciences Publication (January 1, 1968). doi:10.17226/9804.

[21] Mitchell. P.W. “The design of shallow footings on expansive soils”, PhD. Civil Engineering Department, University of Adelaide, (September 1984).

[22] Pidgeon, J.T. “A comparison of existing methods of design of stiffened raft foundations on expansive soils”, seventh Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Accra, (1980).

[23] Vesic A.S. “Beams on elastic subgrade and the Winkler's hypothesis”, Fifth ICSMFE, Vol. 1, (1961): 845-850.

[24] Terzaghi. K.V. “Evaluation of coefficient of subgrade reaction”, Geotechnique, Vol. 5, No. 4, (1955): 297-326.

[25] Do, Q. V., Ahmed Mebarki, J. V. Heck, and Ramdane Ami Saada. "Vulnérabilité des bâtis de maisons individuelles sur sols argileux." In International Symposium" Drought and constructions", SEC2008, (2008):43-52.

[26] Baheddi, M., M. D. Djafarov, and A. Charif. "Design method of flexible continuous footings on swelling clay soils." In 23rd International Mining Congress and Exhibition of Turkey, IMCET 2013, pp. 585-596. (2013): 585-596.