



A Method of Strip Footings Design for Light Structures on Expansive Clays

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ABSTRACT

Shallow stiffened footing, in particular the Vierendeel typology, are considered as a design techniques for structures on expansive soils which have proven their success as challenging solutions; combining economy and safety. The current study is investigating an analytical model for preliminary design of strip footings for light structures on expansive soils, in particular the Vierendeel beam. The developed model is used to calculate, through soil-structure interaction analysis, the algebraic expressions for the bending moment and the footing displacement at any point on the footing. The method is based on a simplification of the clayey ground reaction (P_i) and structure geometry and is derived from an integration of the beam-on-Winkler mound equation. The analytical model is then used to assess the effect of the structure loads on the contact state between the structure and the clayey ground (full or partial contact) as well as the impact of this contact state on the value of the maximum bending moment inside the beam. The results underlines the influence of the construction load on the contact state between the foundation and the swelling soil. The results shows that the bending moment in the footing strongly depends on the contact state between this footing and the clayey ground.

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NOMENCLATURE

P_i	Soil Pressure (KPa)	Δ	Permissible deflection of the footing (m)
y	Free-field soil movement (assumed to occur in the absence of the footing) (m)	L	Footing length (m)
Y	Maximum soil swell (m)	C	Detachment index, which is defined as the ratio of the footing length in contact with the soil to the total length of the footing ($0 \leq C \leq 1$)
f	Footing deformation (m)	E	Young's modulus of the material constituting the beam (KPa)
k	Soil swell stiffness (KPa/m)	I	Quadratic moment of inertia of the cross section (m ⁴).

1. INTRODUCTION

Since engineers realized that special precautions are required when building on expansive soils, many designs of foundations have been developed in an attempt to overcome the negative impact of swelling soils [1-3]. These usually consist of methods that avoid expansive soil layers and load the building onto an underlying stable layer [4]. Shallow stiffened footing, as Vierendeel ones, are also widely used and can be laid directly on expansive soils because of their structural capacity to resist the expansive movement of the ground [5-7].

Actually, due to its simplicity of construction, shallow stiffened footing are considered to be, in many cases, a better cost saving solutions compared to the pile-beam foundation system, especially for lightweight structures such as one and two-story residential and commercial buildings as noted in literature [8, 9]. According to the classification of the Moroccan Guide on design measures for foundations in the North of the Kingdom, a shallow stiffened footing is the best solution for structures built on expansive soils in morocco and over the world. It ensures a high to very high level of protection to the buiding against the differential heave of the foundation subsoils. Negative impacts are avoided or,

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at least, reduced to low cracking of the building, hardly visible on the outside and easily repairable.

However, while the design of a pile-beam foundation may be based on conventional procedures well established in soil mechanics [10], the design of stiffened footings continues to be a major problem in the field of expansive soil mechanics. It is due to considerable complexity in quantifying precisely the behavior of a swelling soil, and modeling of the structure which interacts with this soil movement. This is so difficult that many codes of practice for the design of slabs, such as the Israeli draft code [11], deliberately avoid giving firm recommendations for the design of shallow reinforced footings. Most commonly, strip footings are designed from experience [8].

The objective of this paper is to develop an analytical model for calculating a strip footing, Vierendeel type, resting on a soil mass subjected to swelling movements. The developed model presents theoretical solutions for deflection and moment along the strip, taking into account the phenomenon of clay soil-structure interaction. Although it involves a number of simplifications, e.g. it considers a uniform section strip and assumes that the shape of the soil movement profile beneath the building can be predicted, the method presented herein should provide a basis for preliminary design of strip footings on expansive soils.

The building's mechanical behaviour is modeled using Euler-Bernoulli beam theory, and the soil's behaviour is modeled with a Winkler approach. The focus of this study is on the simplification of the swelling soil reaction expression $P_i(x)$ under the building. Indeed, the literature review revealed a lack of simplified and practical models for determining the reaction of expansive ground along the soil-structural contact surface from the results of simplified laboratory tests. The existing soil – structure interaction models for expansive soils are mostly based on experimental, sometimes heavy, test results [12-14]. and require complex numerical methods by using finite element modeling software [5, 15, 16].

Therefore, the challenge is to use the proposed model to investigate two fundamental questions for the understanding of the complex behavior of the swelling soil-structure system and yet very limited studies exist in the literature:

- ❖ Effects of applied load on the contact state between the footing and the clayey ground (full or partial contact). This aspect is little explored in the scientific literature [5, 8-17].
- ❖ The impact of this contact state on the design of the foundation especially on the value of the maximum bending moment inside the footing *which is an original part of this work.*

This analysis is carried out through a case study of a shallow foundation placed superficially on swelling clay

soil in Ouarzazate city, located in the south of Morocco and subjected to different loading (w) cases ($w = 30$ KPa, 50 Kpa, 100 Kpa, 150 Kpa and 200 KPa).

2. MATERIALS AND METHODS

In the current study, the behavior of the expansive soil-structure system is modeled using the concept of beam on swelling dome proposed by Chen [5],

The most frequent situation of shallow foundations on swelling soils will be examined in this work, namely the swelling of the soil under the center of the foundation (central heave).

In order to take into account, in this model for the worst-case scenario, the foundation seating depth is taken equal to zero.

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 ” (defined in section 4.2. of this paper) of the model presented below, an algorithm has been developed, using the Python language.

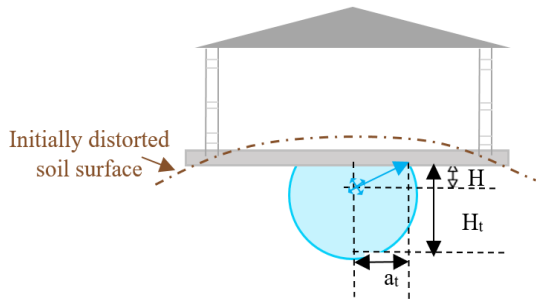
The graphical representations are obtained using autoCAD and Excel software.

2. 1. Description of the Model Figure 1 shows the distance under a building undergoing suction variations caused by humidification of the clayey soil under the effect of a water source located at a depth H below the middle of the foundation.

This change in suction content (Figure 1) leads to a differential settlement of the building and the ground between the center and edges (illustrated in Figures. 2a and 2b), and may in some cases lead to detachment of foundation from clayey ground (Figure 2b).

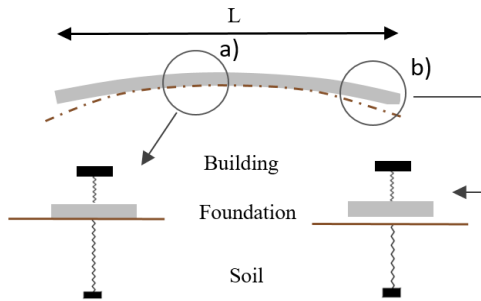
The problem is to determine the distribution of swelling soil reaction under the building, beam deflection and bending moment along the beam for a specified distribution of «free-field» movements.

The current study proposes to analyze the behaviour of a typical foundation, Vierendeel placed superficially on swelling clay soil. This variant consists of intersecting rigidified continuous beams. Each of these Vierendeel beams consists of two continuous members connected by vertical uprights (stiffening posts) embedded and thus forming a square mesh network (Figure 3). For building modeling, the plan of the structure can be divided into overlapping rectangles. So that in the current study, the analysis will be carried out on a rectangular dimensions of length (L) with fixed section, constant rigidity EI ,



Where “at” is a width of the active area and “Ht” is the active depth over which the suction variation is not negligible.

Figure 1. Suction change under the center of the foundation (central heave)



Figures 2. Simplified model for a soil–foundation interaction (a) Contact between soil and foundation (b) detachment of foundation from soil

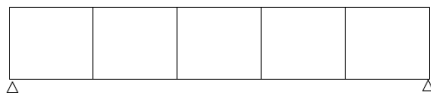


Figure 3. Outline of the Vierendeel type

Young’s modulus E and tolerating a maximum admissible deflection Δ .

In this work, the soil–foundation interaction is investigated by exploiting the model developed by

Farid et al. [23]. The problem considered is shown in Figure 4, which is based on the following points:

- The soil is assumed to be an isotropic, elastic half space and the variability beneath the building of the modulus of reaction, noted k is not considered. The behaviour of the expansive soil-structure system is modelled using the concept of beam on swelling dome proposed by Chen [5].
- To make the analysis general, the beam loading is modelled by 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) and a vertical distribution $P_i(x)$ that corresponds to the swelling soil reaction under the building (Figure 4). For the modelling of the studied system, a linear representation is chosen for the soil reaction under the frame P_i (KPa).

2. 2. Constitutive Equation of the Model and Resolution Procedure

As proposed by Winkler soil model [24], the expression of the ground reaction P_i , induced by the interaction between the swelling soil and the structure, is declined as follows:

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

In the current study, the following expression of the soil reaction modulus k (KPa) determined from the swelling tests is retained :

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

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 .

The distribution along footing for the free deformation of soil, called “swelling domes”, is approximated by the Lytton equation [5, 15-18] as follows:

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

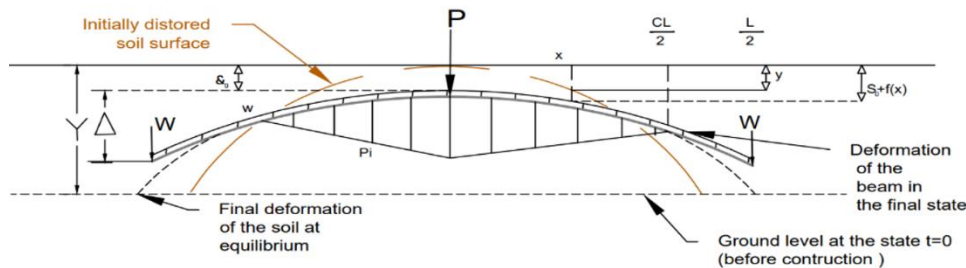


Figure 4. Definition of the building load, ground reaction and the building and ground deflections. For centre Heave (normal or dry season)

The exponent “m” in Equation (3) is an empirical coefficient reflecting the form of the “Swelling dome”, which depends on the length of the foundation (L) and the depth of the active area of the clayey ground (H) (Figure 1) and takes values between 2 and 20. The following expression for the form factor “m” Equation (4), established by Mitchell [8] from analytical solutions of the steady state diffusion equation, is adopted in this study:

$$m = 1,5 \frac{L}{Ht} \tag{4}$$

Inspired by the models of Chen [5] and Mitchell [8] the expression for beam deformation is declined as follows:

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

In Equation (5), an exponent of this equation “a” is an integer.

To model the soil-foundation system response, as a first approximation, the contact state between the ground and the foundation can be considered partial.

At any point of intersection between the soil profile and the footing profile, the soil displacement equals the footing displacement. Equation (6) is used to ensure compatibility between $y(x)$, $f(x)$ and δ_0 : With δ_0 is the settlement at point $x = 0$.

$$f(x) = y(x) - \delta_0 \tag{6}$$

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

According to the principles of the resistance of materials, if the footing is in equilibrium, and has lost contact with the soil over a certain length of footing, then three simultaneous equations are established :

1. In the final state, the superstructure loads must equal the soil forces over the length of footing in contact with the soil:

$$\sum F = P + \frac{w \cdot L}{2} + W = \int_{-CL/2}^{CL/2} Pi(x) dx \tag{7}$$

2. At any point x of the beam, the bending moment due to the external loads and soil reaction must equal to the bending moment corresponding to the curvature of the footing:

$$M(x) = M(x)_{ext} \tag{8}$$

3. The equation of the beam deflection is a second-order differential equation that relates the vertical deflection $f(x)$ and the bending moment $M(x)$ in the x -abscribed cross section:

$$M(x) = - \frac{EI \cdot df(x)^2}{dx^2} \tag{9}$$

4. Taking into account the relationship between the shear force and the bending moment (the Euler-Bernoulli theorem):

$$V(x) = \frac{dM(x)}{dx} \tag{10}$$

The four equations can be used to determine the distribution of soil reaction along the length of footing in contact with the soil, thereby enabling the determination of the bending moment to permit a footing design. Figure 4 shows the applied load (W, w and P), ground reaction ($\pi(x)$) and the building deflection ($f(x)$).

3. RESULTS

The calculation of the swelling soil reaction $\pi(x)$ under the building, induced by the interaction between the swelling soil (modeled by springs) and the structure at static equilibrium, can be obtained by applying the least squares method to the expression of the soil reaction π resulting from Equation (7). The result is declined as follows:

$$Pi(x) = Pi \max \left(\frac{-2}{CL} x + 1 \right) \tag{11}$$

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

where $Pi \max$ denotes the maximum value of the contact pressure of the swelling soil (the wettest zone) and C the detachment index.

When there is detachment, the reaction of the ground $Pi(x)$ is zero throughout.

In a state of final equilibrium, the expressions of bending moment $M(x)$, shear force $V(x)$ and beam deflection are established by applying the relevant boundary conditions to Equations (7), (8) and (9). Equations (12) and (15) give the bending moment, Equations (13) and (16) give the shear force, Equations (14) and (17) give the footing displacement, which when added to δ_0 give the total footing movement:

- For $0 \leq x \leq \frac{CL}{2}$ (contact between the ground and the foundation)

$$M1(x) = \frac{b \cdot Pimax}{3 \cdot CL} x^3 + b \cdot \left(\frac{w}{2} - \frac{Pimax}{2} \right) x^2 + b \cdot \left(\frac{CL \cdot Pimax}{4} - \frac{wL}{2} - W \right) x + b \cdot \left(\frac{wL^2}{8} + \frac{WL}{2} - \frac{(CL)^2 Pimax}{24} \right) \tag{12}$$

$$V1(x) = \frac{Pimax \cdot b}{CL} x^2 + b \cdot (w - Pimax) x + b \cdot \left(\frac{CL \cdot Pimax}{4} - \frac{wL}{2} - W \right) \tag{13}$$

$$f1(x) = \frac{b}{EI} \left(\frac{Pimax}{60 \cdot CL} x^5 - \frac{(Pimax - w)}{24} x^4 + \left(\frac{CL \cdot Pimax}{24} - \frac{wL}{12} - \frac{W}{6} \right) x^3 + \left(\frac{wL^2}{16} + \frac{WL}{4} - \frac{(CL)^2 Pimax}{48} \right) x^2 \right) \tag{14}$$

- While for $\frac{CL}{2} \leq x \leq \frac{L}{2}$ (loss of contact between the soil and the foundation)

$$M_2(x) = \frac{b \cdot w}{2} x^2 - b \cdot \left(\frac{wL}{2} + W\right) x + b \cdot \left(\frac{wL^2}{8} + \frac{WL}{2}\right) \tag{15}$$

$$V_2(x) = V_1 \left(\frac{CL}{2}\right) + w \cdot b \cdot \left(x - \frac{CL}{2}\right) \tag{16}$$

$$f_2(x) = \frac{b}{EI} \left(\frac{w}{24} x^4 - \left(\frac{wL}{12} + \frac{W}{6}\right) x^3 + \left(\frac{wL^2}{16} + \frac{WL}{4}\right) x^2 - \frac{(CL)^2 P_{imax}}{192} x - \frac{3 \cdot P_{imax}}{640} (CL)^4\right) \tag{17}$$

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 (11). Furthermore, L (m) is a footing length and C is the detachment index (0 ≤ C ≤ 1).

4. APPLICATIONS

For the purpose of this article, the results of the model developed above are used to investigate the influence of building load on the contact state between the clayey ground and the foundation first and then the impact of this contact state on the value of the maximum bending moment inside the beam. In this section, a reference case is defined. This case corresponds to a building characterized by a length L = 9 m and having an admissible deflection Δ = 0.009 m. The loading system is reduced to an equivalent uniform load w (KPa) (corresponding to the building self-weight and the loading service). Several loading scenarios will be examined (w = 200 kPa, 150 KPa, 100 KPa, 50 KPa and 30 KPa). The beam is considered placed on the surface (the most critical case) on a layer of soil of the city of Ouarzazate, south of Morocco. It is specified that the studied site is located north of Ouarzazat city, belonging to the High Atlas. The soil mass is characterized by a rigidity k (KPa / m), undergoing a maximum free swelling Y = 0.160 m (Figure 4) and a depth of the active zone Ht (m) under the effect of a water source located at a depth H = 0.5m beneath the middle of the foundation.

4. 1. Effect of the Construction Loads on the Contact State between the Swelling Soil and the Foundation

In this section, the effect of the construction loads on the contact state between the swelling soil and the foundation is evaluated analytically using the method proposed by Farid et al. [17], which is briefly recalled below:

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

- If the total structural load ∑ F_{sup} is less than the value of the "Detachment Factor", which is estimated by $Fd = \frac{Lk}{4} (Y - \Delta)$, then a theoretical loss of contact between

the clayey soil and the foundation can be expected at $x = \frac{CL}{2}$.

The surface rate engaged in the shallow footing - expansive soil interaction can then be equal to CL.

- If not, no detachment occurs and C=1.

Table 1 summarizes values of the soil reaction modulus k (KPa/m), for each value of the equivalent load of the structure w (KPa). The values of the parameter k are estimated from the results of oedometric laboratory tests carried out on samples of swelling soils taken from the experimental site which is the subject of this study (Figure 5), located in Ouarzazate city, by means of Equation (2).

Once all parameters defining the "Detachment factor" are known, the prediction of the swelling soil/ foundation contact state can be made by comparing the respective values of the superstructure forces and the "Detachment factors" for different values of the uniform load w (KPa). The results are synthesized in Table 2.

Thus, perfect soil - foundation contact is expected for structures with a load exceeding w = 166.7 KPa. A value for which the detachment factor and the superstructure forces take the same value Fd = Fsup = 750.1 KN/m. Thus, for less loaded structures (w = 150 KPa; 100 KPa; 50 KPa and 30 KPa) partial separation would occur.

4. 2. Deformations of the Soil-foundation System in the Final Equilibrium State

This analysis is extended below in order to determine the deformations of the soil-foundation system in the final equilibrium state as well as the extent of the soil-structure contact surface under different values of structural loads w (KPa).

TABLE 1. Soil reaction modulus k (KPa) for different values of construction loads

Construction loads w(KPa)	w=200	w=150	w=100	w=50	w=30
Soil reaction modulus k (KPa/m)	2247.2	2142.9	2041	2000	2000

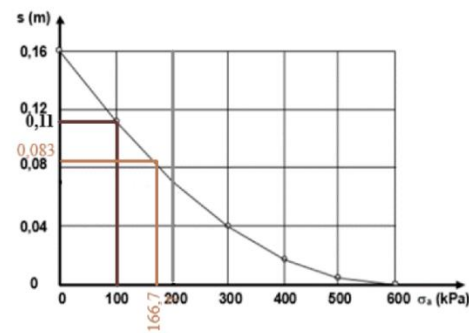


Figure 5. Result of an oedometer swelling test, cited by Ejjjaouani [7]

TABLE 2. Contact state between the foundation and the clayey ground according to the construction loads

Uniform load w (KPa)	200	150	100	50	30
Superstructure forces (KN/m) $F_{sup} = \frac{w \cdot L}{2}$	900	675	450	225	135
Detachment factors (KN/m) $F_d = \frac{Lk}{4} (Y - \Delta)$	763.5	728	679.5	707.8	849.4
Contact state	No lift-off	Lift-off	Lift-off	Lift-off	Lift-off

To do this, the design parameters (m, C and a) which appear in Equations (3), (5), (14) and (17) are evaluated. **Value of the form factor «m»** The form factor “m” is evaluated for an active zone of depth Ht by Equation (4). To remain in conformity with the case treated by Ejjaouani [9], the most critical case with an active zone depth Ht equal to 2.8 m (corresponding to a width of the active zone at equal to half of the half beam) is treated. The depth of the active zone Ht (illustrated in Figure 1) can be evaluated by the following expression:

$$H_t = H + \sqrt{at^2 + H^2} = 2,80 \text{ m}$$

So, according to Equation (4):

$$m = \frac{1,5 \cdot 9}{2,8} = 4,82$$

Values of parameters «C» and «a» Values of the detachment index "C" and the parameter "a" can be conveniently undertaken by Newton’s method.

In the current study, for the determination of values of parameters “C” and “a”, an algorithm has been developed using the Python language. Indeed, an iterative procedure is carried out and it starts by assuming an initial value to the parameter "a", then calculating the value of “C” by Equation (8) (using the expression of the soil reaction $P_i(x)$ given by Equation (11)). The values of the footing deformation $f(x)$ at two different points of the beam, obtained by using Equations (5) and (14), allow the assumed value of «a» to be checked from the following equation:

$$a = \ln\left(\frac{f_1(x_1)}{f_1(x_2)}\right) / \ln\left(\frac{x_1}{x_2}\right) \quad (18)$$

The correct value of “a” is then obtained by a process of trial and error, which can be undertaken quickly on a small programmable calculator.

Figure 6 summarizes the algorithm explained above for obtaining the values of parameters «C» and «a».

Table 3 summarizes values of parameters “C” and “a”, obtained by using the Python language, as well as the extent of the contact between the clayey soil and the

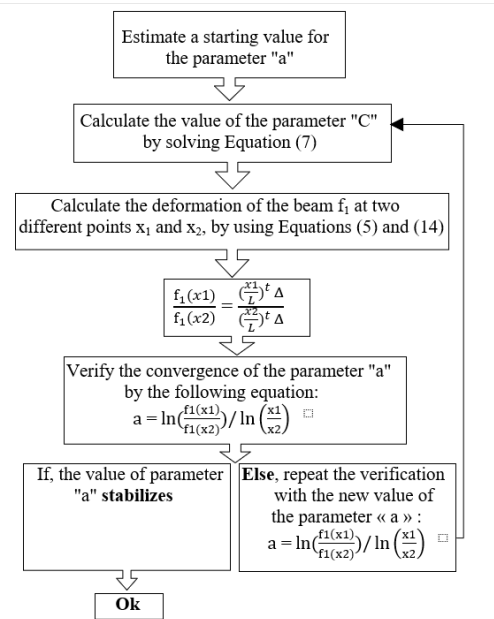


Figure 6. The proposed algorithm for obtaining the values of parameters « C » and « a »

TABLE 3. Parameter values "C" and "a" and the soil-foundation contact extent according to the load of the structure

Structural load w (KPa)	150	100	50	30
α	1.91	1.91	1.91	1.90
Detachment index C (0 ≤ C ≤ 1)	0.99	0.93	0.83	0.77
Contact length: swelling ground / footing CL (m)	8.91	8.37	7.47	6.93

foundation for different loading scenarios w (150 KPa; 100 KPa; 50 KPa and 30 KPa), by adopting the approach described above.

Figures 7 to 10 show the final deformations of soil and beam resulting from the swelling soil-structure interaction under different values of w.

For the range of values of k, Y and Δ considered in this analysis, the results of this study illustrated in Figures 7 to 10 show that the extent of the soil-structure contact area increases when the building load w increases. Thus, the console part of the beam is shortened with the load; going from 1.035m for a structure loaded with 30 KPa (Figure 10) to less than 5 cm for a more heavy structure, loaded more than 150KPa (Figure 7).

Also, these Figures show that the final building deformation (due to load and suction variation) increases when the building load w increases. Meanwhile a structure loaded at more than 150 KPa would consume more than 15 cm of the free swelling of the clayey soil (before construction), a light structure loaded at less than

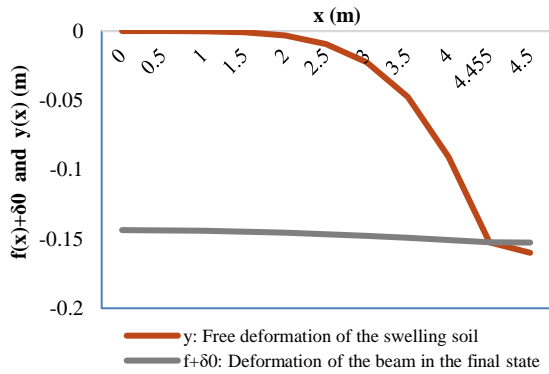


Figure 7. Final state of the soil and the beam loaded at $w = 150$ KPa

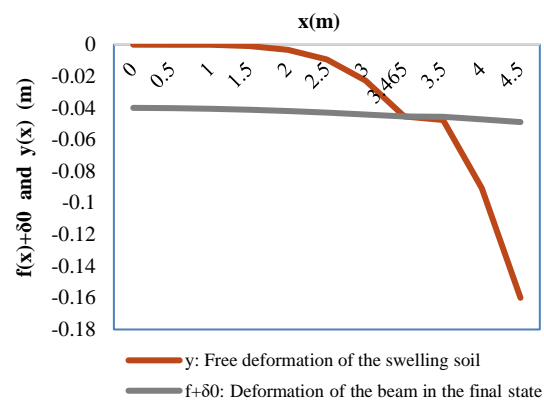


Figure 10. Final state of the soil and the beam loaded at $w = 30$ KPa

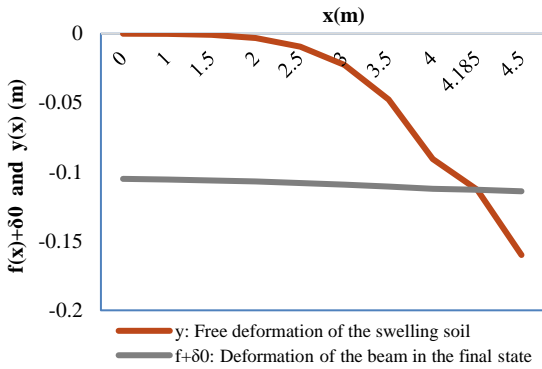


Figure 8. Final state of the soil and the beam loaded at $w = 100$ KPa

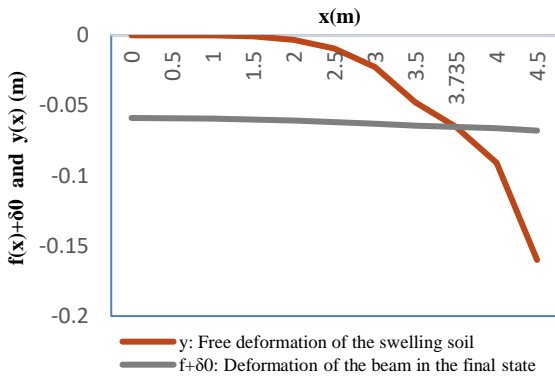


Figure 9. Final state of the soil and the beam loaded at $w = 50$ KPa

50 MPa would consume less than 6 cm of the free swelling of the clay soil.

4. 3. Impact of the Swelling Ground - Foundation Contact State on the Bending Moment inside the Footing

In this section, the impact of the swelling soil /footing contact state on the design of the foundation

is examined by comparing the maximum bending moment induced inside the footing in the two scenarios: "possibility of detachment of the foundation from the clayey ground" and "perfect contact" according to the approach explained below.

a. By adopting the model tolerating the detachment of the structure from the ground (detachment of the foundation from the ground object of this study, for structures loaded less than 166.7 KPa), the maximum bending moments M_{max} inside the beam is determined using Equations (12) and (15), developed in this article.

The distribution of the bending moment inside the beam, resulting from the application of Equations (12) and (15), is presented in Figure 11 below, for the different values of the equivalent load w (30 KPa, 50 KPa, 100 KPa and 150 KPa).

This figure shows that the resulting bending moment inside the beam (due to load and suction variation) is maximum in the mid-section of the beam and becomes zero at the edges of the foundation.

This figure also shows that the resulting bending moment inside the beam increases with increasing weight of the structure. So that a structure loaded at less than 30MPa would have a maximum moment of less than 147 KN.m while a foundation loaded at more than 150 KPa would be stressed by a maximum moment exceeding 513 MPa.

b. By adopting the idea that the clayey soil / footing contact is always maintained (independently of the load of the structure w (KPa)), the bending moment $M(x)$ induced inside the footing will be calculated, for the same values of workloads used in the previous calculations ($w = 150$ KPa; 100 KPa; 50 KPa and 30 KPa), using the model developed by Ejjaouani [7], which exploits the Filonenko-Borodich model.

The maximum values of the bending moments induced in the beam in the two scenarios (contact with or without separation) are summarized in Table 4 below:

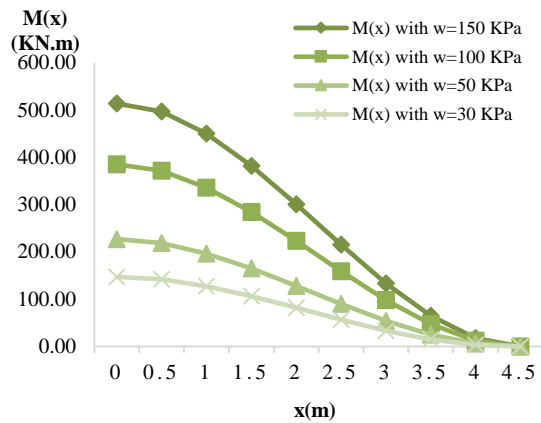


Figure 11. Bending moment along the loaded half-beam at $w = 30$ KPa, 50 KPa, 100 KPa and 150 KPa

TABLE 4. Maximum values of bending moments: “perfect contact” scenario and “possibility of separation” scenario

Structural load w (KPa)	200	150	100	50	30
Maximum bending moment (KN.m)					
«Perfect contact» scenario	455.62	341.72	227.82	113.91	68.34
Model H. Ejjaouani [9]					
Maximum bending moment (KN.m)					
«Possibility of separation» scenario	455.62	513.80	385.17	227.18	147.21
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Deviation (%)	0	33	41	50	53

The results of this analysis show a difference between the determined values of the maximum bending moments inside the beam in the two scenarios. This difference increases with the decrease in the value of the work load. Thus, for structures loaded more than 150 KPa a deviation of less than 33% can be expected while a deviation exceeding 50% can be considered for light structures ($w \leq 50$ KPa).

5. DISCUSSION

A method of analysis is developed for the design of shallow footing on expansive soil, suitable for routine use by practitioners (design offices and geotechnicians). An approach that is both safe and reliable, although it involves a number of simplifying assumptions as justified above.

The swelling of the soil under the center of the foundation (central heave) was examined in this work. The most frequent and an inevitable situation of swelling of the clayey soil because of the variation in the water state of the clay soil under the building due to the thermosmosis effect due to the thermal gradient between the soil in the middle of the building footprint and at the ends.

The example treated as an application of the method in this article brings out the following conclusions:

This study clearly reveals that the contact state between the foundation and the swelling soil depends on the structure load. The lighter a structure is, the more likely detachment occurs. Reversely, the increase in the load of the structure always tends to widen the footprint of soil-structure contact. This result is in agreement with the results of the parametric study detailed by Farid et al. [17].

The same tendency of a decrease in the contact surface between the swelling soil and the structure compared to the decrease in the weight of the foundation structure is observed.

On the other hand, the approach assuming that “the soil-structure contact is always maintained because of the plastic behaviour of the supporting clay soil” as explained by Ejjaouani [7] does not prove to be generally applicable, at least for light structures (loaded to less than 166 MPa, under the conditions of the case study discussed above).

The method of this article makes it possible to precisely define the length of the swelling soil - foundation contact length (equal to CL), a key parameter in the design study of any foundation. This is possible thanks to a numerical resolution of Equations 5, 8, 11 and 14 by Newton's method. In this work, this analysis was conducted by using the Python language to create functions with fewer lines of code. It is well known that the Python language has one of the most mature package managers (PyPI) and is the most widely used language in modern data science by both beginners and experts alike.

The comparison of maximum values of bending moments induced in footing in the case of a perfect contact scenario (independently of the value of the structure load) and in the second case where the detachment of the structure from the support soil is tolerated shows that: the bending moment in the footing strongly depends on the contact state between this footing and the clayey ground. Indeed, the second scenario leads to a more conservative maximum bending moment. Also, it was noted that the difference between the determined values of the maximum bending moments in the 2 scenarios increases with the decrease in the value of the load of the structure. Thus, a deviation exceeding 50% can be considered for light structures ($w \leq 50$ KPa). These results are in harmony with the recommendations of BRAB [15], which specifies that the greater the soil

support is given to the beam the lower the bending moment induced in the beam is.

As illustrated in Figure 16, the decrease in bending moment with decreasing structural loads is clearly illustrated. This is consistent with the fact that the bending moment induced in the footing, under the effect of the swelling soil-structure interaction, is only the result of the difference between the load of the structure and the pressure of swelling ground contact.

It should be noted that in this study, the soil and building parameters (k , Y , Δ , L and w) were assumed to be independent, although they could be correlated for real buildings. This possible correlation was not taken into account.

In addition, the single-layer code, adopted in this work (assuming a uniform behaviour of the soil over the entire height of the clay layer), can lead to a detachment of the structure even for an average frame load. Especially since in this approach, the effect of the foundation bed depth is not taken into account. Therefore, one would expect that the method proposed in this article would be improved by adopting a multi-layered approach taking into account the evolution of the suction depth and the bedding depth of the foundation in order to achieve a less conservative bending moment.

6. CONCLUSION AND OUTLOOKS

A new soil-structure interaction analytical model was developed for the design of a shallow footing on expansive soil, especially the Vienendeel Type. The behavior of swelling soils was modeled using the concept of linearization of the clayey ground reaction integrated into a soil-structure interaction model that is based on the idealized Winkler model for the soil and an elastic Euler-Bernoulli beam concept for the building. The model can be used to calculate the the final deflection of a building and the bending moment at any point on the footing.

The method presented herein, although it involves a number of simplifications, should provide a basis for preliminary design of strip footings on expansive soils. Most commonly designed from experience.

The analytical model was then used to investigate the effects of applied load on the contact state between the footing and the clayey ground (full or partial contact) and the impact of this contact state on the design of the foundation especially on the value of the maximum bending moment inside the footing which is an original part of this work which is an original part of this work. The results showed that the value of the maximum bending moment inside the foundation is very influenced by the contact state between the foundation and the clayey ground retained in the analysis of the system.

This research could be extended in the future by exploiting a more complete and precise database on the

damaged houses. The developed model could be improved by adopting a multi-layered approach taking into account the evolution of the suction depth and the bedding depth of the foundation.

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Persian Abstract

چکیده

پایه های مستحکم کم عمق، به ویژه گونه شناسی **Vierendeel**، به عنوان یک تکنیک طراحی برای سازه های روی خاک وسیع در نظر گرفته می شوند که موفقیت خود را به عنوان راه حل های چالش برانگیز ثابت کرده اند. تلفیق اقتصاد و ایمنی مطالعه حاضر در حال بررسی یک مدل تحلیلی برای طراحی اولیه پایه های نواری برای سازه های سبک در خاکهای وسیع، به ویژه تیر **Vierendeel** است. مدل توسعه یافته برای محاسبه، از طریق تجزیه و تحلیل تعامل خاک و ساختار، عبارات جبری برای لحظه خمش و جابجایی پایه در هر نقطه از پایه استفاده می شود. این روش بر ساده سازی واکنش خاک رس (**Pi**) و هندسه ساختار استوار است و از ادغام معادله تپه تیر بر وینکلر مشتق شده است. سپس از مدل تحلیلی برای ارزیابی تأثیر بارهای سازه بر وضعیت تماس بین سازه و سطح خاک رس (تماس کامل یا جزئی) و همچنین تأثیر این حالت تماس بر مقدار حداکثر گشتاور خمش داخل استفاده می شود. پرتو. نتایج بر تأثیر بار ساختمانی بر وضعیت تماس بین فونداسیون و خاک متورم تأکید می کند. نتایج نشان می دهد که گشتاور خمش در پایه به شدت به وضعیت تماس بین این پایه و سطح خاک رس بستگی دارد.
