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Swelling and collapse behavior of expansive marl and its implications in foundation engineering

Dimitrios Loukidis[1]*, *Georgia* Lazarou[1], *Ploutarchos* Tzampoglou[1], and *Thrasivoulos* Stylianou[1]

[1] Department of Civil & Environmental Engineering, University of Cyprus, Nicosia, Cyprus

Abstract. Expansive soils increase their volume upon wetting, but under high vertical stresses may exhibit collapse, with the latter aspect being rather overlooked in foundation engineering. Oedometer swelling/collapse tests on expansive Pliocene marls of various calcium carbonate content and plasticity index sampled from Nicosia, Cyprus, indicate that, unlike the free swelling strain, the swelling pressure is rather insensitive to the initial degree of saturation. Consequently, significant collapse strains upon wetting are not unlikely to occur in practical situations. The paper discusses the implications of this behavior in the case of shallow foundations and proposes methods of analysis. Under certain conditions, foundation design based on settlement calculations that use as input the fully saturated soil properties may be unconservative and supported structures may be exposed to severe risk of damage. For the design of mat foundations, stepwise distributions of the equivalent modulus of subgrade reaction across the mat as a function of the average bearing pressure are proposed based on the results of coupled finite element simulations. These distributions allow prediction of the peak bending moments produced at the end of the wet and dry seasons due to ground swelling and shrinkage, respectively, for the climatic conditions of Cyprus.

1 Introduction

Marls are clayey geomaterials that have a significant calcium carbonate content (25% to 75%). Despite the strong presence of $CaCO_3$ in their matrix and the bonding (cementation) it provides, marls can be highly expansive depending on the composition of their clay fraction. Examples of expansive marls are frequent around the Mediterranean basin, e.g. Greece [1], Spain [2] and Cyprus [3].

Expansive ground constitutes a major source of problems to buildings and infrastructure, resulting annually in billions of dollars in damage cost worldwide [4]. Building damage can be caused by i) seasonal fluctuations of ground moisture due to rainfall during the wet season and evapotranspiration in the dry season, ii) long-term changes in ground moisture due irrigation and changes in the surrounding vegetation, and iii) by water leakage from pipes. Except in the latter case, the moisture changes and the associated ground heave or settlement concern only the columns at the perimeter of the building. This gives rise to differential heave/settlement that imposes distortion to the structural frames, leading to various forms and degrees of damages, ranging from problems of architectural nature, such as cracking of infill walls, window/door jamming, e.t.c. (exceedance of serviceability limit state) to cracks in the structural frame (exceedance of ultimate limit state).

It is well established that spread footings constitute a poor choice in the case of swelling clays [5,6] because such a foundation system lacks the necessary stiffness to resist the differential movements. Mat foundations, with or without stiffening ribs, constitute the state-of-practice for buildings founded on expansive ground. Nonetheless, they must be properly designed [7-10] to ensure that they have the required capacity to resist the differential contact pressures and the resulting bending moments without yielding or losing significant part of their stiffness.

The present paper discusses the potential of damage development in low-rise and mid-rise buildings under the prism of results from swelling/collapse oedometer tests on expansive Nicosia marl. Subsequently, a method for the structural analysis of mat foundations in Nicosia marl relying on varying across the mat the modulus of subgrade reaction is presented.

2 Swelling/collapse of Nicosia marl

The expansive marls of the Nicosia geological formation (Pliocene) have been deposited in a shallow marine environment and a major part of their clay fraction consists of montmorillonite [3,11]. The marls exhibit significant heterogeneity with respect to clay fraction CF (<2μm) and $CaCO_3$ content. As a result, there are locations and depths in which the marl is moderately plastic and medium expansive, and others in

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* Corresponding author: loukidis@ucy.ac.cy

which the marl is of high plasticity and consequently very highly expansive (Fig.1).

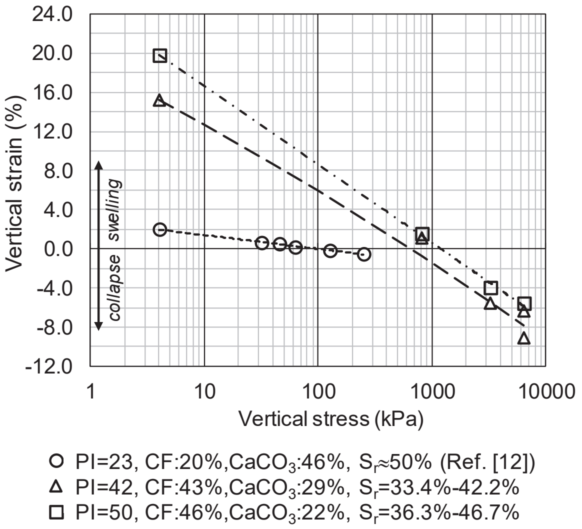

Fig. 1. Results of inundation tests on Nicosia marls of different calcite content and plasticity.

Fig. 2 presents the results from series of swelling/collapse tests performed in a conventional oedometer on undisturbed samples of three marls of the Nicosia formation with different clay and calcite content. Each sample was first allowed to settle under a target vertical stress and partially saturated conditions for two days. The oedometer cells were sealed with cling film during that period in order to minimise loss of moisture to the atmosphere. Then, the samples were inundated with distilled water, keeping the vertical stress constant, and the vertical deformation was recorded (method *wetting-after-loading tests on multiple specimens* in ASTM D4546-08 terminology). For each marl, three batches of specimens were prepared with respect to the initial degree of saturation S_r: i) at their as-sampled natural water content, ii) dried in desiccators filled with saturated NaCl solution, iii) wetted in desiccators filled with distilled water.

The marl of Fig. 2a is of medium-to-high expansiveness due to its high calcite content and low clay content, with the free swelling strain ε_{fsw} (assumed herein as the vertical strain developing under a sitting load corresponding to 4kPa vertical stress) at initial S_r around 30% being only 3.8%. Increasing the clay fraction CF and decreasing calcite content results in a significant increase in the marl expansiveness (Fig. 2b,c). As expected, the free swelling strain decreases with increasing initial S_r. Yet, the swelling pressure σ_{sp}, i.e. the value of the applied vertical stress at which the behavior changes from swelling to collapse, seems to be insensitive to changes in initial S_r. As the initial S_r increases, the loci in Fig. 2 appear to rotate around a pivot point roughly corresponding to σ_{sp}. Consequently, at vertical stresses exceeding σ_{sp}, large collapse strains may develop if the marl is initially in a strongly desiccated state.

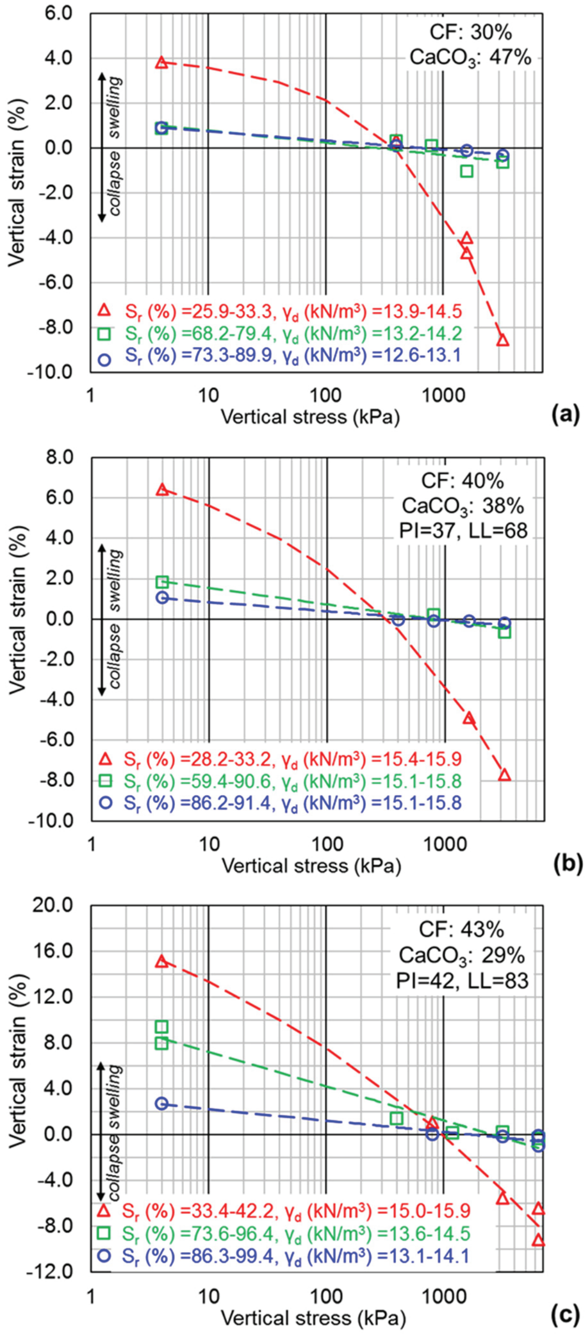

Fig. 2. Effect of initial saturation state on swelling/collapse response during inundation.

3 Differential heave/settlement of spread footings

This section examines the development of differential heave/settlement Δw due to seasonal ground wetting and the associated angular distortion β that is expected for RC or steel frame buildings founded on footings in Nicosia marl. To calculate the heave/settlement w_m of a footing [6,13], the soil profile is divided in n sublayers with thickness h_i (i=1…n) down to the depth of the active zone (Fig. 3).

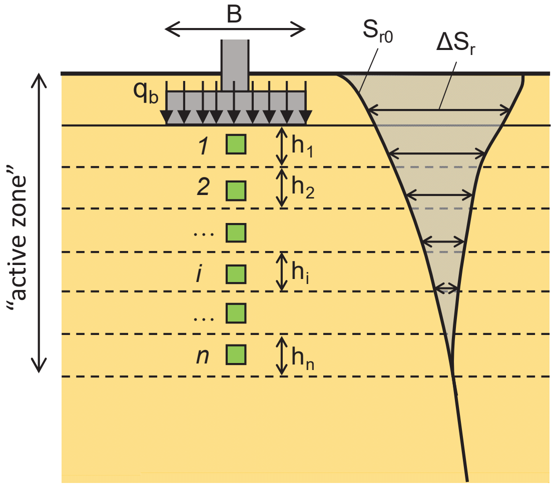

Fig. 3. Schematic of simplified calculation of footing heave/settlement due to ground moisture changes.

The active zone is the upper part of the ground profile in which the soil moisture is affected by rainfall and evapotranspiration. The footing movement w_m can be calculated based on oedometer inundation test results using the following equation [6]:

$$w_m = \sum_{i=1}^{n} \varepsilon_{v,i} a_i h_i \tag{1}$$

where $\varepsilon_{v,i}$ is the vertical strain that would develop if S_r increases from an initial value S_{r0} to 1.0 (100%). Because most of the active zone will remain below full saturation during the lifetime of the structure, ε_v is multiplied by a reduction factor α assuming proportionality between volumetric strain and the expected increase ΔS_r in the degree of saturation [4]:

$$a_i = \frac{\Delta S_{r,i}}{1 - S_{r0,i}} \tag{2}$$

Given that the swelling/collapse loci in Figs. 1 & 2 can be approximated by straight lines, $\varepsilon_{v,i}$ can be calculated based on the inundation test results as follows:

$$\varepsilon_{v,i} = C_H \log\left(\sigma_{sp} / \sigma_{v,i}\right) \tag{3}$$

where $\sigma_{v,i}$ is the vertical stress in the middle of sublayer *i*, constituting the sum of the geostatic stress plus the stress increase caused by the application of the footing bearing pressure q_b, and C_H is the heave index [13]. In the case of Nicosia marl, the swelling pressure σ_{sp} could be treated as a material constant and eq. (3) can be rewritten as follows:

$$\varepsilon_{v,i} = \varepsilon_{fsw,i} \frac{\log\left(\sigma_{sp} / \sigma_{v,i}\right)}{\log\left(\sigma_{sp} / \sigma_{fsw}\right)} \tag{4}$$

where ε_{fsw} is the free swelling strain and σ_{fsw} is the vertical stress at which ε_{fsw} is measured in the oedometer (herein 4kPa). Assuming that ε_{fsw} is roughly a linear function of the initial degree of saturation S_{r0} [4], it can be estimated as follows:

$$\varepsilon_{fsw,i} = \varepsilon_{fsw,ref} \frac{S_{r0,i} - 1}{S_{r0,ref} - 1} \tag{5}$$

where $\varepsilon_{fsw,ref}$ is a reference free swelling strain measured for a reference initial degree of saturation $S_{r0,ref}$.

Seasonal ground moisture changes do not penetrate horizontally more than 5m under a building [12]. Considering a typical frame span L_s of at least 5m, the largest Δw is expected at the spans having one column at the perimeter of the building and the other being an inner column, for which w_m can be assumed equal to zero. Hence, the differential heave/settlement due to seasonal ground moisture changes is practically equal to the w_m of the column at the perimeter. The total differential settlement is obtained by adding to this quantity the expected differential settlement in the absence of ground moisture change, which is herein assumed equal to half of the footing load-induced settlement w_0 calculated using the elastic modulus of the marl at degree of saturation equal to S_{r0}. Hence, the angular distortion β is calculated as:

$$\beta = \frac{\Delta w}{L_s} = \frac{|w_m| + 0.5 w_0}{L_s} \tag{6}$$

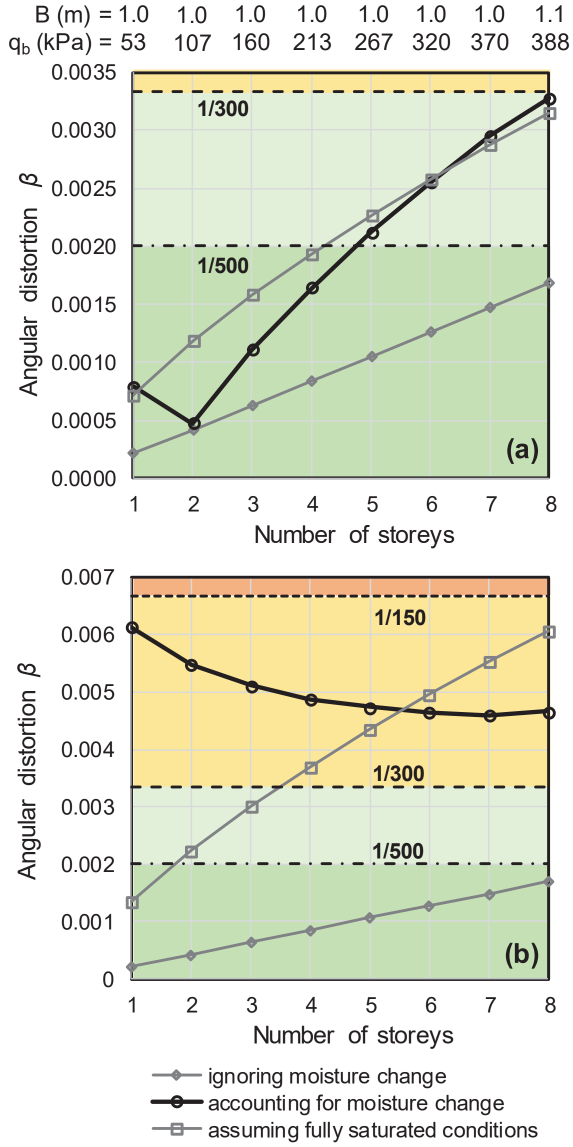

Fig. 4. Expected angular distortion for buildings founded on strip footings in a) medium expansive and b) very highly expansive Nicosia marl.

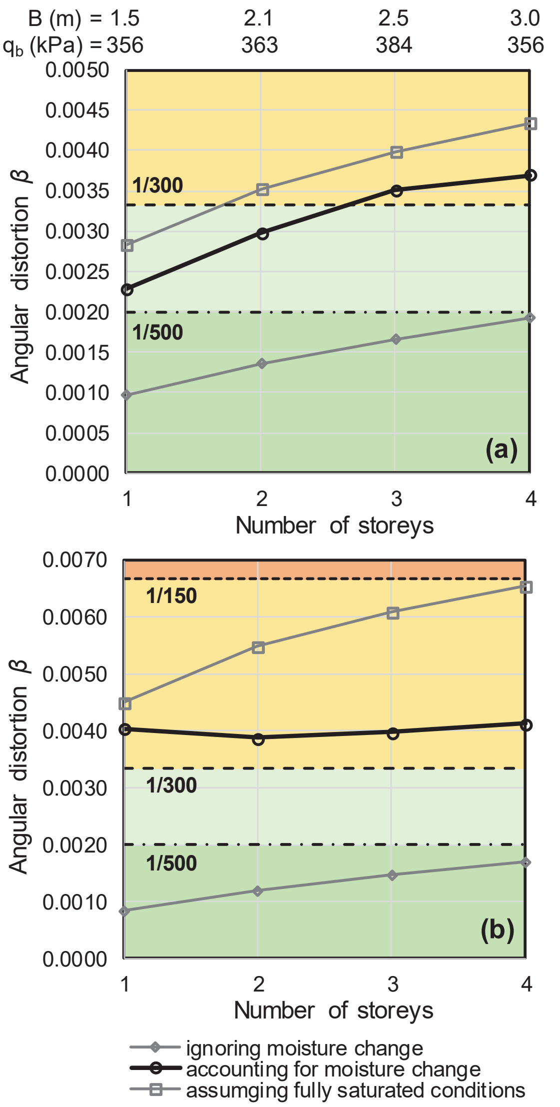

Fig. 5. Expected angular distortion for buildings founded on square spread footings in in a) medium expansive and b) very highly expansive Nicosia marl.

Figs. 4 and 5 present β values calculated using eqs. (1)-(6) for two example case: medium expansive marl with $\varepsilon_{fsw,ref}$=2% at $S_{r0,ref}$=55% and σ_{sp}=90kPa [12] and very highly expansive marl with $\varepsilon_{fsw,ref}$=9% at $S_{r0,ref}$=80% and σ_{sp}=1000kPa. Two foundation configurations are considered in each case: buildings supported on parallel rows of strip footings and buildings supported on square spread footings, both resting at 0.5m depth from the ground surface. The frame span L_s is equal to 5m and each column is assumed to carry 200kN per storey. The strip footing width is set equal to 1m, expect in the case of 8 storeys in order to not exceed an allowable bearing pressure of 390kPa that is consistent with the marl's strength. The square footing width varies with the number of storeys for the bearing pressure q_b to be close to the allowable one. Calculations are done for realistic scenarios of S_r for each marl case (Fig. 6) which produce free-field heave equal to 2cm and 6cm for medium and very highly expansive marl, respectively.

Figs. 4 & 5 show also β values i) if any potential increase in S_r is neglected and settlement calculations are done with elastic modulus values corresponding to degree of saturation equal to S_{r0}, ii) assuming that the ground is permanently fully saturated (immediate settlement plus consolidation settlement calculated using fully saturated compressibility coefficient values). The latter constitutes the classical conservative practice in the case of non-expansive ground. It can be seen that, irrespectively of the number of storeys, buildings on either strip or square footings in very highly expansive marl (Fig. 4b and 5b) will develop β values that clearly exceed the limit value of 1/300 beyond which wall cracking is expected according to the building database of Skempton & MacDonald [14]. This happens even for buildings with 4 to 8 storeys because of the high swelling potential at bearing pressures much smaller than the swelling pressure.

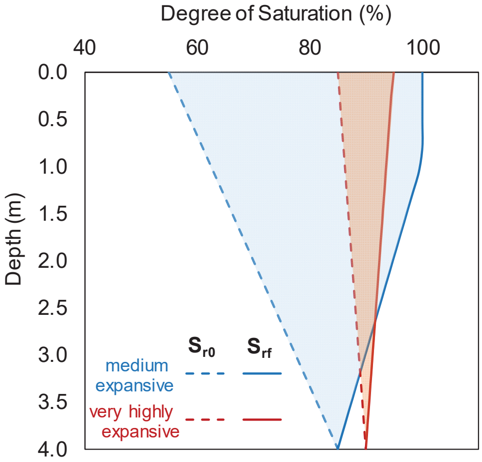

Fig. 6. Assumed profiles of initial (S_{r0}) and final (S_{rf}) degree of saturation.

In the case of medium expansive marl (Figs. 4a & 5a), the differential settlement and the associated angular distortion are due to collapse under the footing at the building perimeter (except for 1-storey building on strip footing, in which case the q_b is smaller than the swelling pressure). As a consequence, the potential of exceeding distortion limits increases with increasing number of storeys.

It is interesting to note that, if calculations are done using elastic moduli corresponding to unsaturated conditions and ignoring moisture increase, the β values are below the limiting value of 1/500 used in standard design practice [6] and adopted by Eurocode 7. On the other hand, performing settlement calculations assuming permanent fully saturated conditions generally produces β values larger than when accounting for moisture changes. However, this is not always true, as seen in Fig. 4.

4 Bending of mat foundations

In the previous section it was demonstrated that it is quite difficult for footings to accommodate deformations caused by moisture-induced soil volume changes. Hence, a mat is the foundation type of choice for expansive ground, provided though that it is properly designed to withstand the effects of soil swelling and shrinkage. This section presents a method of analysis proposed for the design of mats on expansive Nicosia marl using the concept of a spatially varying modulus of subgrade reaction *k*.

4.1 Coupled FE analyses of mat-soil interaction

For the purpose of deriving *k* distributions that would allow prediction of the bending moments caused by soil swelling/shrinkage, coupled finite element analyses (FEA) of mat-expansive ground interaction were performed using the commercial software Plaxis 2D. A simple one-dimensional constitutive model [15] was used in FEA in order to obtain soil volume changes due to rainfall infiltration and evaporation. The climatic input was consistent with that of Nicosia for a typical hydrological year.

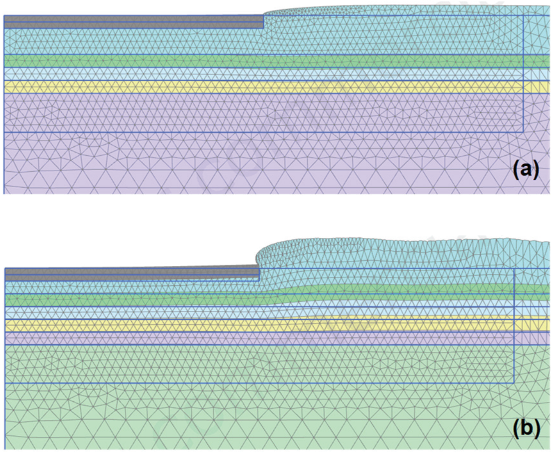

Fig. 7. Deformed mesh (exaggerated) from coupled FEA of mat foundation: a) medium expansive, b) very highly expansive marl.

Fig. 7 shows the deformed mesh at the end of the wet season (March) for marls with different degree of expansiveness. It can be seen that the mat is bent upwards due to the swelling of the foundation soil that lies close to the its perimeter. The opposite happens at the end of the dry season (September), when the mat loses support close to its perimeter due to soil shrinkage. Hence, a mat must be designed for both scenarios. Fig. 8 compares the bending moment diagrams developing in a mat 0.5m thick loaded with uniformly distributed load in the 12kPa to 120kPa range. For medium expansive marl (Fig. 8a) and average bearing pressure $q_{b,ave}$=12kPa, soil swelling (March) produces a maximum positive moment (bottom fiber in tension) that is 60% larger compared to the initial conditions (absence of soil swelling/shrinkage). On the other hand, for $q_{b,ave}$ equal to 60kPa and 120kPa there is a decrease of 40% and 45%, respectively, due to the suppression of the swelling tendency by the larger load. The most critical case is the one corresponding to the end of the dry season (September). However, as the imposed load increases, the peak negative moments decrease substantially. The effect of load magnitude is limited in the case of very highly expansive marl (Fig. 8b), both in terms of positive and negative peak moments. This is because the swelling pressure of this marl is 1MPa, much larger than the load range 12-120kPa.

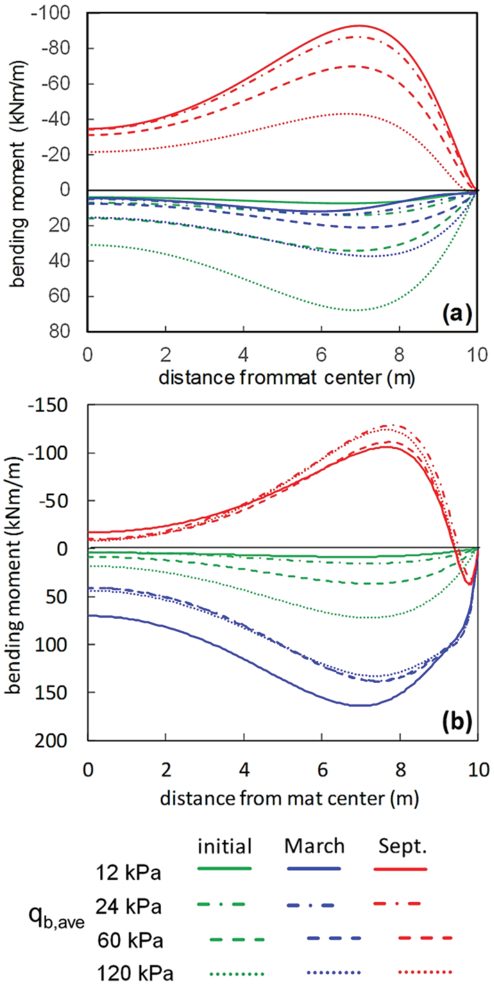

Fig. 8. Bending moments developing in a mat 0.5m thick in: a) medium expansive marl, b) very highly expansive marl.

4.2 Equivalent modulus of subgrade reaction distribution for mat design

One way to reproduce in structural analysis the additional bending caused by soil swelling and shrinkage is to use suitable stepwise distributions for the modulus of subgrade reaction *k*, with a central region having value k_1 and an outer zone of width L_e having k_2 (Fig. 9). For wet season analysis, k_2 needs to be much larger than k_1 in order to produce the extra positive bending moments caused by soil swelling. Oppositely, k_2 must be smaller than k_1 to simulate the partial loss of support at the mat edge in a dry season analysis. Given that the tendency for swelling decreases as the pressure exerted to the soil increases, k_2 is set to be an exponential function of $q_{b,ave}$ as follows:

$$k_2 = k_1\left[c_1 \exp\left(c_2\left(\frac{q_{b,ave}}{p_a}\right)^n\right)+c_3\right] \qquad (7)$$

where p_a=100kPa and c_1,c_2,c_3 and *n* are fitting constants that were established based on the results of the coupled FEA and the values of which are shown in Table 1. The modulus at the central zone, k_1, is constant and equal to a value k_{ref}, except for the case of wet season analysis in highly expansive marl. It was found that a k_{ref} value equal to 10000kPa/m is suitable for Nicosia marls irrespectively of their expansiveness. According to eq. (7) and the values in Table 1, as $q_{b,ave}$ increases, k_2 converges to the value of $4k_1$, i.e. the value that holds for an analysis in absence of soil swelling/shrinkage. Finally, it turns out that L_e needs to be much larger in dry season analysis (3.5m-4.5m) than in wet season analysis (0.5m-1.5m).

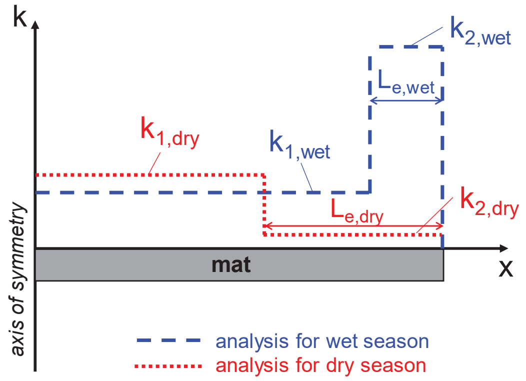

Fig. 9. Proposed two-step distributions of modulus of subgrade reaction *k* for analysis of mat foundation in expansive marl.

Table 1. Parameters for proposed two-step distribution for modulus of subgrade reaction.

Analysis	Medium expansive	Very highly expansive
No swelling/ shrinkage	$k_1=k_{ref}$ $c_1=c_2=0$, $c_3=4$ $L_e=0.5$m	$k_1=k_{ref}$ $c_1=c_2=0$, $c_3=4$ $L_e=0.5$m
Wet season	$k_1=k_{ref}$ $c_1=4.26$, $c_2=-12$, $c_3=4$, $n=1$ $L_e=0.5$m	$k_1=k_{ref}[1-\exp(-0.5q/p_a)]$ $c_1=54$, $c_2=-6.5$ $c_3=4$, $n=1$ $L_e=1.5$m
Dry season	$k_1=k_{ref}$ $c_1=-4.26$ $c_2=-0.63$, $c_3=4$ $n=1$, $L_e=3.5$m	$k_1=k_{ref}$ $c_1=-4.0$, $c_2=-0.075$ $c_3=4$, $n=1.2$ $L_e=4.5$m

5 Conclusions

Inundation tests in the oedometer reveal that, apart from the tendency for swelling that depends on its plasticity and composition, Nicosia marl has also a potential for developing significant collapse strains when the overburden pressure exceeds the swelling pressure. Consequently, damages may develop in buildings supported by footings on medium expansive marl due to collapse upon wetting. For very highly expansive marl, damages are caused due to soil expansion in both low- and mid-rise buildings supported on footings.

Mat foundations need to be properly analysed and designed to withstand the adverse effects of soil swelling in the wet season, as well shrinkage in the dry season. This could be achieved by performing structural analyses for wet season using enhanced subgrade reaction values near the perimeter. Oppositely, for dry season analysis, the modulus of subgrade reaction needs to be smaller in a perimetrical zone than in the central zone.

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