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Effect of K0 on the settlement of a raft foundation: a numerical study

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ABSTRACT: Prediction of settlement remains one of the most studied problems in geotechnical engineering. Even though the use of numerical analysis tools such as Finite Element Method has enabled an improved and convenient means of settlement prediction, the quality of a prediction depends on the efficacy of the numerical analyses and soil constitutive models. Initial ground condition could significantly influence the mechanical behaviour of natural clays in numerical analysis. Due to complexity of stress history undergone by soil deposits, it remains difficult to reconstruct its initial state of stress. In the context of everyday routine design, reliable site measurements of K0 are rarity, and its value remains one of the most difficult parameters to determine. In this paper, a set of 3D finite element analysis cases has been carried out using finite element software Plaxis3D to investigate the effects of K0 on the settlement of raft foundation of varying sizes on London Clay. Issues associated with numerically calculated settlement for different values of K0 are discussed.

Keywords: Settlement; Raft Foundation; Finite Element; Earth Pressure Coefficient

1 INTRODUCTION

Prediction of settlement of geotechnical structures remains one of the most studied problems in geotechnical engineering. Even though the use of numerical analysis tool such as Finite Element has become popular which has enabled an improved and convenient means of settlement prediction, the quality of any prediction depends on the efficacy of the numerical model and parameters adopted for the soil strata in question.

Among other factors, initial ground condition, also called “Greenfield” (O'Brien, et al., 2020) could significantly influence the mechanical behaviour of natural clays, and without which the stress state of soil cannot be properly defined, particularly when advanced soil constitutive models are used. Initial ground condition is the unchanged existing initial stress state which exist within the ground because geological formation history (i.e., without man-made interventions). It is also influenced by the weight of soil and water conditions. Due to complexity of the stress history undergone by a soil deposit, it remains difficult to reconstruct its initial state of stress.

In most geotechnical numerical analysis software, the initial in-situ effective stress state of a soil deposit (of a horizontal ground surface) is typically expressed in terms of at rest coefficient of earth pressure (K0), as an input to the analysis, which represents the ratio of effective horizontal σ'_h to vertical stresses σ'_v. It should be noted that this procedure is particularly applicable to situations with horizontal soil layers and levelled water surface (Bentley, 2020).

A number of direct (in-situ) and indirect (laboratory) methods have been developed for determining the horizontal stress in clayey soils, (Boháč, et al., 2013). Most notable of the direct methods are the pressuremeter and Marchetti dilatometer tests, however the use of these methods is still questionable due to soil disturbance and installation issues. It was also shown that the effective horizontal stress could be measured in the laboratory by averaging the capillary pressure of undisturbed samples, (Skempton, 1961), however it was later shown that such method could result in underestimating value of K0 due to changes in mean effective stresses and pore water pressures produced during sampling and specimen preparation (Doran, et al., 2000).

London Clay is known to be heavily overconsolidated and its in-situ K0 is known to vary with depth, from maximum value of up to 3 within shallower depths (up to 10 metres) and gradually stabilises at about 1 at depth increases. In numerical analysis it is usually prescribed a value of 1.0 to 1.5, e.g., (Addenbrooke, et al., 1997) and (Jurecic, et al., 2013). Several previous studies have considered the effect of initial stress state represented via the K0 approach. These studies particularly focused on problems of tunnelling, deep foundations, stability analysis of cuts and excavations. For instance, a three dimensional (3D) finite element analysis study by (Franzius, et al., 2005) investigated the influence of soil anisotropy and K0 on the ground surface settlement due to tunnelling in London Clay. The study compared the results using K0 =0.5 and K0 =1.5 and reported that the filed data of tunnel settlement trough were better predicted using the lower, and unrealistic, value of K0 of London Clay. However, the low value resulted in an unrealistic value of volume loss. The value of K0 also affected the shape and magnitude of settlement. (G. Lee, 2002) conducted a series of 3D elasto-plastic coupled-consolidation finite element analyses using ABAQUS to study the effects of K0 and stiffness anisotropy on ground settlements due to tunnelling in London Clay . The study concluded that surface ground settlements are governed by the combined effects of K0 and anisotropic stiffness, and that the effects of K0 are relatively more important than stiffness anisotropy on the calculations of ground settlements.

In the context of everyday routine design practice, reliable site measurements of K0 are rarity. In addition, although London Clay is among the most geotechnically studied soils, its K0 value remains one of the most difficult parameters to determine, (Hight, et al., 2003). As this problem is less studied for the case of surface foundations, it is worth examining whether the reported effect of variation of K0 exists, as is the case in the problems of tunnelling and retaining structures,

In this paper, a suite of 33no. 3D finite element analysis cases have been carried out to investigate the effects of K0 on the settlement of raft foundations of varying sizes on London Clay. Although settlement of shallow foundations, especially of symmetric dimensions, is not necessarily a 3D problem, 3D analysis allows for considering anisotropic soil properties, such as permeability, which could influence settlement predictions.

2 ANALYSIS

2.1 Soil constitutive model and material parameters

The finite element program Plaxis 3D (Bentley, 2020) was used to model raft foundation with coupled time-dependent analysis of deformation and excess pore pressures. A representative finite element mesh for a hypothetical equidimensional wished-in-place raft foundation is shown in Figure 1. The numerical model considers 10-noded tetrahedral elements to model the soil and 6-node plate element with an added interface element (using a strength reduction factor Rinter=0.67 to allow for a proper modelling of soil-structure interaction) to model the foundation (Plaxis(a), 2020). Standard Plaxis 3D fixities are applied to the boundaries of the geometry model. The bottom of the FE model is fully fixed in all directions whereas the side boundaries are normally fixed and free in the vertical z-direction, and the ground surface is free in all directions. FE mesh was made finer around the foundation footprint and coarser farther from it. The lateral and vertical boundaries of the FE mesh were kept at 2.5 times the raft width B where mesh size increase had no further effect on settlement results.

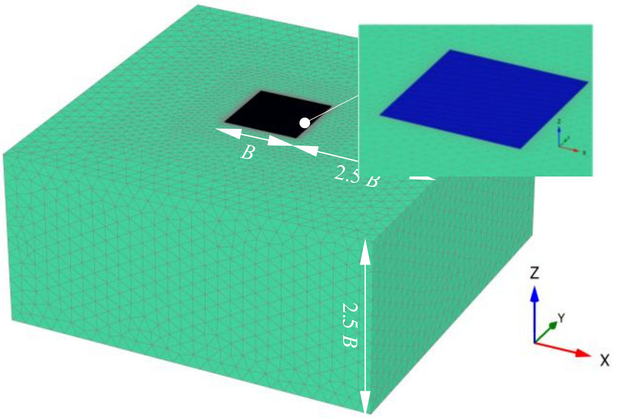

Figure 1. Plaxis 3D Finite Element mesh

For simplicity, the ground profile comprises a single layer of generic London Clay which was modelled using the Hardening Soil (HS) model (Schanz, et al., 1999). The HS model is an advanced elastoplastic model for the simulation of soil behaviour which includes several features relevant to practical applications including stress dependence of stiffness, soil deviatoric and volumetric hardening (plastic straining), dilatancy and unloading/reloading stiffness. The HS model requires a number of stiffness parameters which are defined in effective stress in addition to peak friction angle and effective cohesion which define the failure surface (Mohr-Coulomb failure criterion). The formulation of the Hardening Soil model is the hyperbolic relationship between the vertical strain, ε1, and the deviatoric stress, q, in primary triaxial loading, Figure 2. For the purpose of this study, typical values for London Clay from published literature have been used (Obrzud, et al., 2018), see Table 1. Water table is assumed at ground surface level with a hydrostatic porewater pressure. In addition, the raft foundation with equal dimensions (width=length =B) and a thickness of 1.00 metre is modelled as a linear elastic material which characteristic parameters are as described in Table 2.

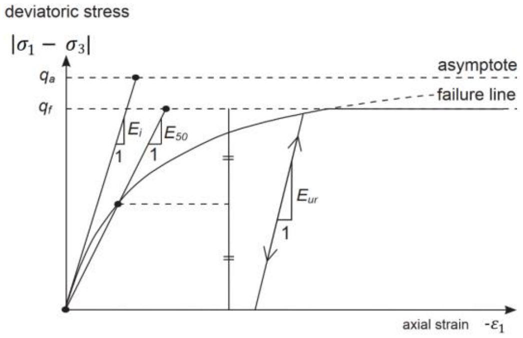

Figure 2. Hyperbolic stress-strain relation in primary loading for a standard drained triaxial test (Plaxis(b), 2020)

Table 1. Hardening Soil constitutive model parameters for London Clay, (Obrzud, et al., 2018)

Parameter	**Value**

Strength parameters	φ'_p=25°, c'=5kPa
Dilatancy angle	ψ=12.5°
Unit weight	$\gamma_{sat} = 20$ kN/m^3
Permeability coefficient m/s	k_x=k_y= 1.0E-09, k_z= 1.0E-10
Secant stiffness (50 % of the maximum deviatoric stress) Oedometer (tangent) stiffness MPa	$E_{50}^{ref} = E_{oed}^{ref} = 35$
Unloading-reloading stiffness MPa	E_{ur}^{ref}=75
Stress dependency power	m= 0.75
Reference stress kPa	$P^{ref} = 360$
Poisson's ratio	ν'_{ur}=0.2
Analysis Phases	Initial Phase, undrained plastic calculation phase and Consolidation phase
Initial Stress Generation	K0-Procedure

Table 2. Foundation characteristics

Parameter	Value
Dimensions	10 x 10 x 1 m 20 x 20 x 1 m 30 x 30 x 1 m
Unit weight kN/m^3	γ = 24
Young's Modulus (uncracked section) GPa	30

2.2 Parametric study

Computational power readily available today enables performing parametric studies with relative ease. The current study considered analysis cases for a range of K0 values between 0.5 and 3 each for 3 raft foundation size cases B=[10, 20, 30] metre. Plaxis uses K0-Procedure to generate the initial stress state at the beginning of the calculation. For the HS model K0 is calculated using Jaky's formula (K0^{nc}) adjusted for inclusion of OCR. Hence, the initial stress state is a function of K0 as well as OCR. OCR values have been selected to return the K0 range of values used in this parametric study.

Foundation loading are applied as uniformly distributed surface loading (UDL = 100, 150 and 200 kPa respectively) and selected as such that lumped factor of safety against bearing failure is ~3.

For validation, a comparison is made, see Figure 3, against settlement results from 3D finite element study presented by Giannopoulos (Giannopoulos, 2011) on the raft foundation of Hiscocks House, London. The raft is resting on London Clay up to 24m bgl with 0.9m thick and an equivallent square width of B_{eq} =~29m with an avergae K0 value ranging of 2.

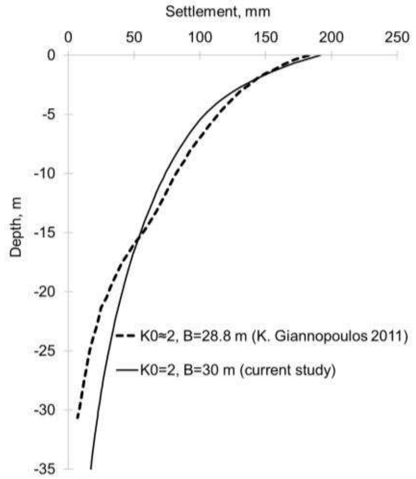

Figure 3. Settlement profile with depth in the long term for the raft foundation

3 RESULTS AND DESCUSSION

Figure 4 (a, b, and c) presents analysis results of the total foundation settlement with time for the range of K0 and foundation dimensions 10m, 20m, and 30m respectively. As would be expected, an inverse relationship exists between K0 and the magnitude of settlement, the smaller the former the greater the latter. This is understandably due to the decrease in soil confining lateral stress associated with lower K0 values. This tendency is independent of foundation size and loading magnitude considered, despite increase in the magnitude of settlement. It could be also noticed that the greater the foundation dimension and loading, the greater the rate by which the settlement increases with decrease of K0.

From the three figures, it appears that majority of settlement would have occurred 5-8 years post construction. This is within the typical timeframe of total settlement for rafts on London Clay, e.g., as in the case of Clapham Road, Hurley Road (Block II) and King Edward's Road buildings rafts where monitoring data showed that majority settlement occurred within 5-6 years, (Morton, et al., 1975). However, the same publication reports a high level of variability in consolidation times in other case studies on London Clay (90% consolidation reached up to 20 years).

Figure 5 (a, b, and c) show plots of settlement against depth for the three raft sizes and show the expected increase of influence depth as foundation size increases. For raft widths 10m, 20 and 30m, settlement seems to diminish at a decreasing depth/width ratio of ~2, ~1.5 and ~1.3 respectively. However, settlement is reducing more rapidly with depth for smaller and less loaded rafts. Similar observation to Figure 4, the greater the raft size, the greater the settlement increase rate with increase of K0.

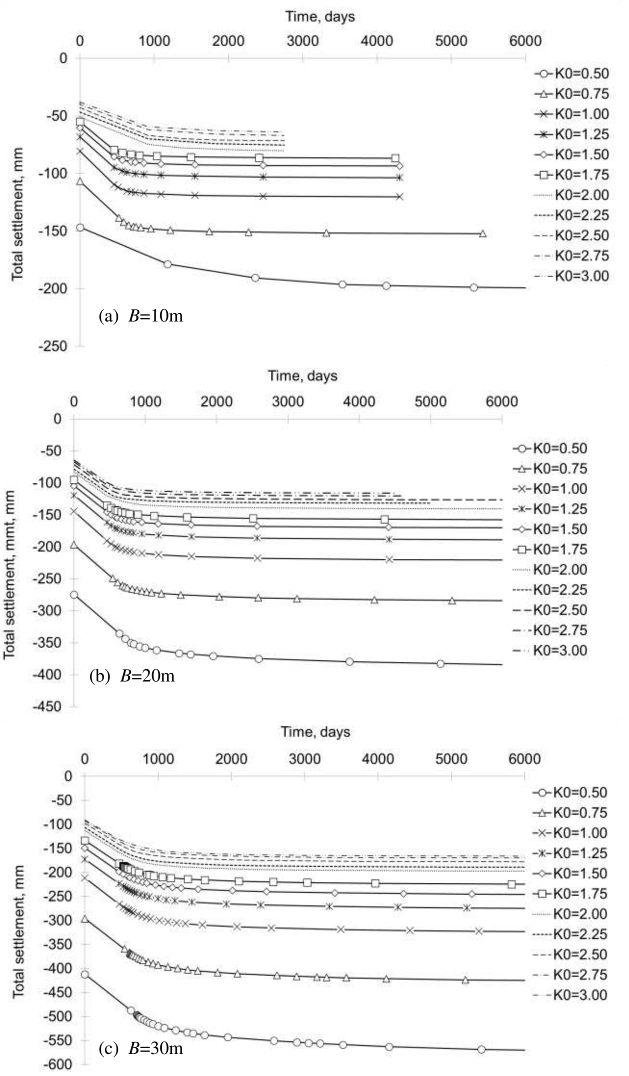

Figure 4. Time-total foundation settlement profile with change in K0 and foundation dimension

Given the above it is possible to plot the maximum long term settlement of each raft size case with the change in K0 as shown in Figure 6. The maximum raft settlement could then be represented with a power function fit as a in terms of K0 and foundation width as shown in Equation (1).

$$S_{B_i} = \left(\frac{B_i}{10}\right) \left[c_1 K_0^{-1} + c_2\right] \ , \qquad (1)$$

for $10 \leq B \leq 30$

where $c_1 = 92$, $c_2 = 30$ and , $i=[1,2,3]$

Expanding the settlement-K0-foundation size relationship above, it is possible to produce a contour plot of the variation of raft settlement with K0 and raft size as shown in Figure 7. Equation 1 and contour plot could be useful tools obtain first-order estimate of total settlement of raft foundations on London Clay for any value of K0 between 0.5 and 3 and any raft size between 10m to 30m.

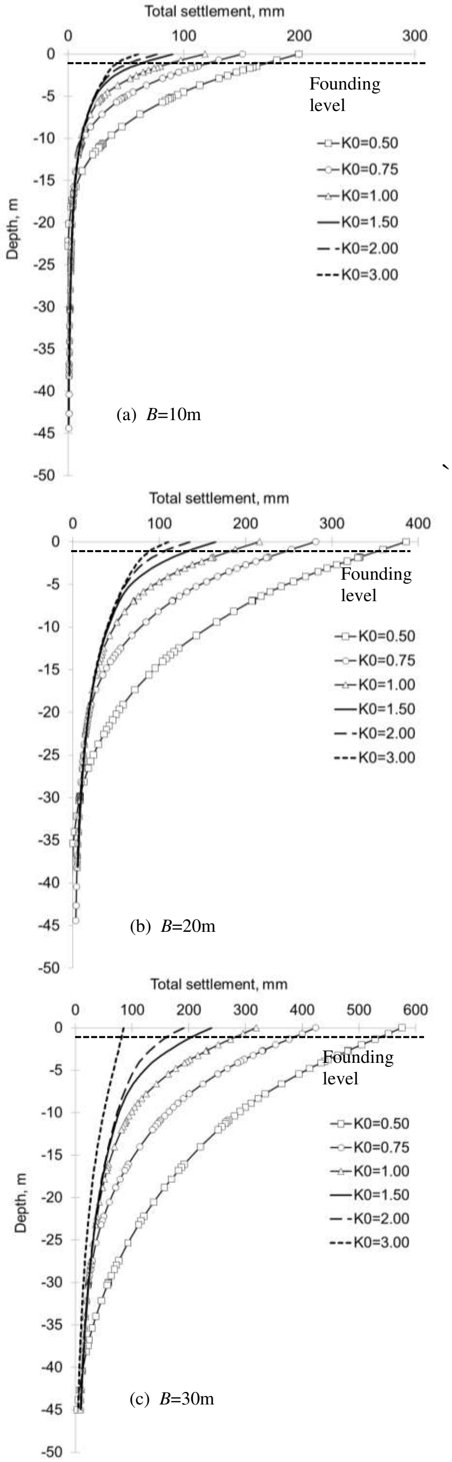

Figure 5. Total foundation settlement profile with change in K0

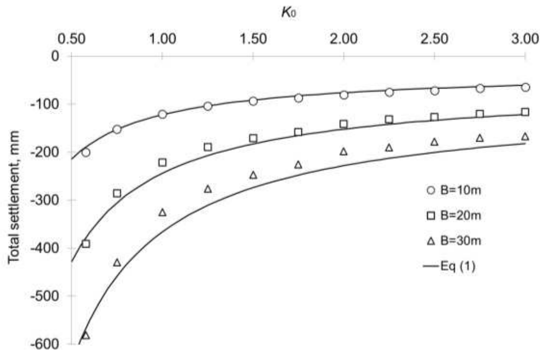

Figure 6. Change in total long term foundation settlement with K0 and foundation dimension

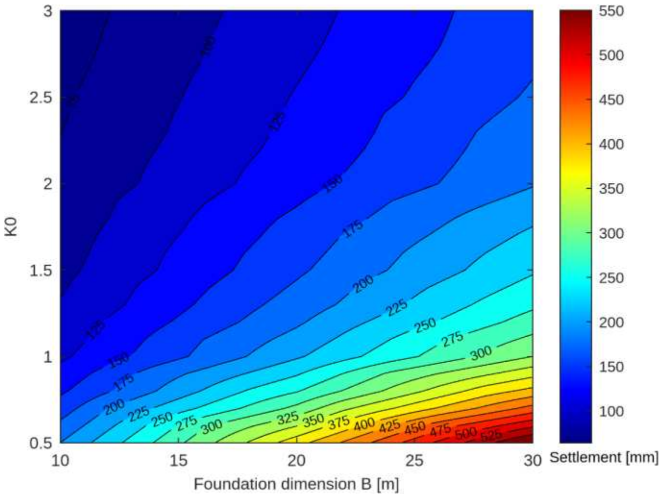

Figure 7. Maximum foundation settlement changes with K0 *and foundation dimension*

Based all of the above, irrespective of foundation size, the important effect of K0 value on the settlement prediction is evident.

In the HS model, in Plaxis, the formulation of soil stiffness (in all its forms: secant E_{50}, oedometer E_{oed} and unloading-reloading E_{ur}) is a function of the minor principal stress σ'_3 e.g., Equation (2).

$$E_{50} = E_{50}^{ref} \left(\frac{c\cos(\phi) - \sigma_3' \sin(\phi)}{c\ \cos(\phi) - p^{ref} \sin(\phi)} \right)^{m} , \qquad (2)$$

The value of initial stiffness E_{i} is related to E_{50} with the following Equation (3).

$$E_i = \frac{2E_{50}}{2 - R_f} , \qquad (3)$$

where R_{f} is a failure ratio between ultimate deviatoric stress q_{f} and asymptotic value of the shear strength q_{a} which typically taken as 0.9. The confining or lateral soil stress is in turn a function of the constant value of K0 which is selected at the beginning of analysis. To demonstrate the effect of K0 on soil stiffness as modelled in the HS model, it is possible using Eq2 and Eq3 to compute the undrained stiffness E_{u} for the different values of K0. Figure 8 shows the variation of undrained stiffness with mean normal effective stress derived using the HS equations and those back-analysed for various sites on London Clay (Burland, 1989). Sensitivity of modelled stiffness to the selected value of K0 is evident. In comparison to field studies, it could be said that a reliable value of K0 for London Clay for numerical analysis could be vary between 1 and 2. Similar observation is reported by Hight, et al., 2003, 2006., although values up to 3 are reported at depth < 5m bgl at Heathrow T5 and Ashford Common.

Several years of monitoring of two structures of similar area (20m x 20m approx.) founded on rafts in London Clay, namely Clapham Road and Hurley Road Block II (Morton, et al., 1975) showed settlement of about 100 mm. In comparison to the current study, the maximum settlement for the *B*=20m case, computed maximum settlement below foundation level is 356mm, 185 mm, 109mm and 90mm for K0= 0.5, 1, 2 and 3 respectively.

As aforementioned, measured values of K0 for London Clay lies in the range of up to 3 at shallow depth and gradually decrease with depth to an average value of 1. In numerical analysis software such as Plaxis, a single constant value of K0 is used which means that K0 is averaged over depth. Repeating the analysis for the same case of *B*=20m with soil layers with K0 of 2.5 for depth 0m to 10m, K0 of 2 for depth of 10m to 20m and K0 of 1.5 for depth of 20m to 30m resulted in average settlement of about 100mm which is closer to observed value.

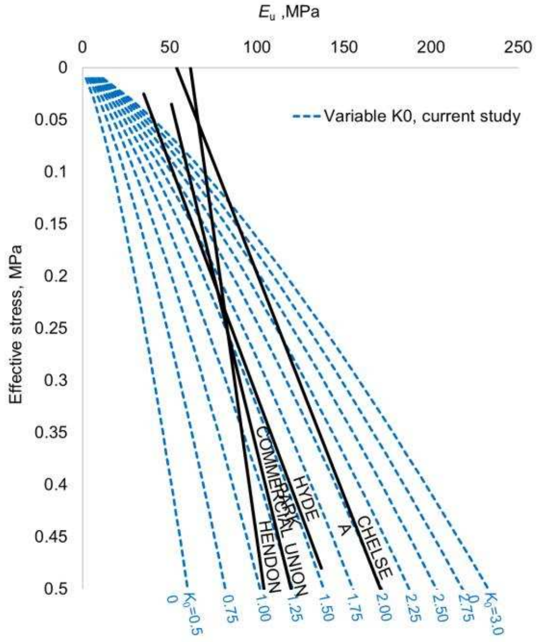

Figure 8. Variation of undrained stiffness of London Clay with effective stress (parametric study vs. field measurement)

4 CONCLUSIONS

This paper investigated the settlement of raft foundation on over-consolidated clay using finite element software Plaxis3D to investigate the effects of K0 on the settlement. Irrespective of foundation sizes, the effect of K0 value on the settlement prediction was evident For raft widths 10m, 20m and 30m, settlement seems to diminish at a decreasing depth/width ratio. However, settlement reduced more rapidly with depth for smaller and lightly loaded foundations. When the maximum settlement for each raft size were plotted against the change in K0, the maximum raft settlement could be represented with a power fit as a function of K0 and foundation width. Assumed value of K0 influenced the predicted settlement substantially. Averaging of K0 over depth adopted in numerical analysis software could lead to inaccurate predictions rafts settlement in London Clay. Hence in order to improve numerical settlement prediction, a variable value of K0 increasing with depth should be used.

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