Using soft soil models in geotechnical engineering: a review paper

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Abstract. Soil is considered a complicated material as, in general, the behavior under loading is non-linear in addition it is anisotropic material and its behavior is time-dependent. Various models were developed in the method of finite element for modeling the behavior of soil under different loading cases, and it must be known that no constitutive model is available that can simulate completely the actual soil behavior under all conditions. This paper attempts to investigate the soft soil model and present a discussion about the advantages and disadvantages for the purpose of giving an overview, and discussing the main finding of the previous studies regarding using the Soft Soil model in the numerical analysis of geotechnical engineering problems and applications. In this research, it was observed from the previous studies that the relation between the modified compression index (λ^*) and unloading index (κ^*) is from (5 to 10). The Soft Soil model gives a stiffer stress-strain behavior compared to Hardening model. Using this model for compressible soils needs a longer calculation time than other models as the material stiffness matrix was included in each calculation step. It shows satisfactory results in the analysis of the settlement of immediate and consolidation cases of foundation in clayey soil than the model of Mohr-Coulomb. Keywords: Finite Element, Soft soil model, Clayey soil.

1 Introduction

In geotechnical engineering, various models were developed in the finite element analysis for modeling the behavior of soil under different loading types, also for analysis of soil-structure interaction, these models ranged from simple to complicate. In fact, the actual soil behavior is very complex due to their component, so it shows different responses under loading in addition to the anisotropy and its behavior is time-dependent, in the analysis of soil behaviors there are several models available in the finite element software. Moreover, each model has advantages and disadvantages according to soil state, loading type, boundary condition.

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Hence, in this study, it was investigated the numerical analysis using the model of soft soil, as it is appropriate for high-compressible soils, such as normally consolidated clay, clayey silts, and peat.

2 Soft soil model

The model of Soft Soil is one of the constitutive models available in the finite element software; in this model, the relation is logarithmic between the volumetric strain (εv) and the average effective stress (P'). In the case of compression isotropic, with a normal consolidation line, the relation as shown [1]:

$$\varepsilon_v - \varepsilon_v^0 = -\lambda^* \, ln\left(\frac{p' + c\cot\phi}{p^o + c\cot\phi}\right) \qquad (1)$$

Where:
ε_v^0 : Initial volumetric strain
λ^* : modified compression index
p^0 : initial mean effective stress
However, in case of the unloading and reloading case, the behavior is different and as shown:

$$\varepsilon_v^e - \varepsilon_v^{e0} = -\kappa^* \, ln\left(\frac{p' + c\cot\phi}{p^o + c\cot\phi}\right) \qquad (2)$$

Where,
κ^* : compression index for of the unloading and reloading case
ε_v^e : Volumetric elastic strain
ε_v^{e0} : Initial volumetric elastic strain.
The difference between modified compression index (λ^*) and compression index for the unloading and reloading case (κ^*) is clarified in Figure (1). Moreover, from Figure (2) it can be noted that the yield contour is in the form of an ellipse, and the slope of the line of critical state equal (M). However, in the Soft Soil model, the critical state is not necessary to be related to the failure. Instead, a failure criterion of Mohr-Coulomb is considered for obtaining a more realistic state of failure. The theory of this model is similar to the Cam-Clay model, there was an unlimited number of ellipses and the extent of the ellipse is determined by the mean pre-consolidation effective pressure along the axis.

The parameters of modified compression index (λ^*) and unloading index (κ^*) could be obtained from a one-dimensional consolidation test for unloading and reloading case when plotting the strain-stress diagram in logarithm scale. The slope of the primary compression line reveals the modified compression index (λ^*), and for the unloading case (swelling), it produces the unloading index (κ^*). Note that these parameters can be obtained from compression index (cc) and swelling index (cs) from the following relation [1]:

$$\lambda^* = \frac{cc}{2.3\,(1+e)} \qquad (3)$$

$$\kappa *= \frac{2 * \; cs}{2.3\,(1+e)} \qquad (4)$$

If the result of oedometer test is not available there was an empirical relationship suggested related to the value of modified compression index (λ^*) and unloading /reloading index (κ^*) as the following relation [2]:

$$\lambda^* = 0.3\, P.I \qquad (5)$$
$$\lambda^* = 0.2\,(L.L - 0.1) \qquad (6)$$

In general, the relation between the value of the two factors, modified compression index (λ*) and compression unloading index (κ*) as shown [2]:

$$\frac{\lambda^*}{\kappa *} = 2.5 \quad to \quad 7 \qquad (7)$$

The important properties of the Soft Soil model can be summarized as:

1. The behavior at failure is similar to the model of Mohr-Coulomb.
2. The yield surface has coincided with a modified model of Cam-Clay concerning the flow rule for strain in a plastic state.
3. The parameters of stiffness can be considered from the test of oedometer test.

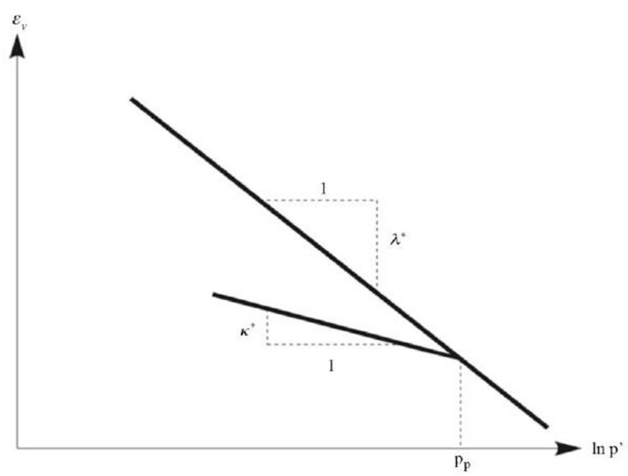

Fig. 1. Relationship of volumetric strain versus mean effective stress. [1]

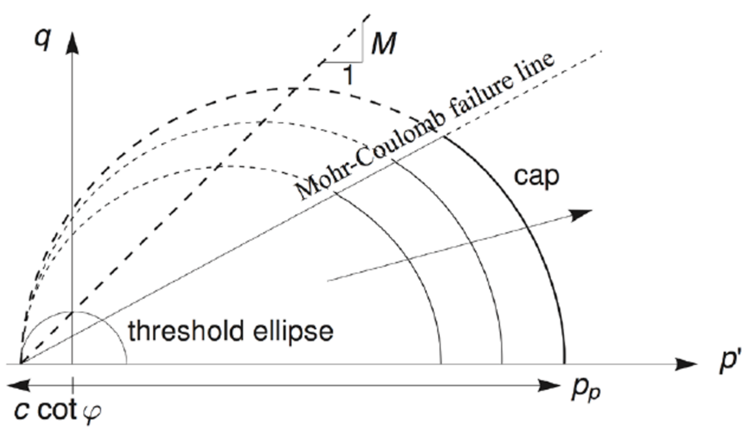

Fig. 2. Soft Soil yield surface according to p'-q diagram.[1]

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2.1 Advantages and disadvantages of the model of Soft Soil

The advantages of the model of soft soil according to Kahlstrom [3] are:

1. The stiffness is dependent on stress with a logarithmic relationship.
2. The model can distinguish between the loading and unloading state.
3. It was taking into account the stress at pre-consolidation.

While the main disadvantages can be summarized as:

1. This model is suitable for normally consolidated (or near) clay, especially in soft case.
2. Not take into account the creep state.
3. More convenient for stress paths at a compression state.
4. Not taking into account the case of anisotropy soil state.

2.2 Input parameters

The main parameters considered of the soft soil model are given in Table (1), while the advanced parameters as shown in Table (2).

Table 1. The main input parameters used in the Soft Soil.

Parameters	Symbol	Unit
Soil cohesion	c	kPa
Friction angle	Ø	^{o}
Angle of dilatancy	ψ	^{o}
Modified compression index	λ^*	-
Unloading and reloading index	κ^*	-
Secondary compression index	m	-
Poisson's Ratio	ν	-
Exponential Power	m	-

Table 2. The advanced parameters used in the Soft Soil soil.

Parameters	Symbol	Unit
Poisson's Ratio	ν	-
Lateral stress coefficient	K_o	-
Coefficient of permeability	k_x , k_y	m/day

3 Previous studies

In general, the model of Soft Soil is adopted primarily in the studies of settlement analysis of embankments, filings, foundations etc. such as the study of Mesri et al.(1994) [4] , Indraratna et al., 1994 [5], Cudny and Neher (1998) [6] and Karstunen et al. (2005) [7].

According to the study of Vermeer and Neher (1999) [8], the 1-dimension strain of creep oedometer model was extended to a 3-dimension state of stress-strain by incorporating the concepts of the model of Modified Cam-Clay (Soft Soil) and visco-plasticity. It is observed that using this model can simulate the results of tests very well, also the general observation of the ratio between the modified compression index (λ^*) and compression unloading index (κ^*) is in the range between (5 to 10) .

Koch (2009) [9] conducted a laboratory investigation of Transdanubian Clay to assess the input parameters of Hardening and Soft Soil model. About 150 tests of oedometer are analyzed in order to evaluate the determination of these parameters. Based on the result analysis, the ratio between between the modified compression index (λ^*) and unloading /reloading index (κ^*) is ($\lambda^* = 5.7\ \kappa^*$), where this is in agreement with the range of recommendation of Plaxis software manual [1].

Elsawy (2013) considered the model of soft soil creep for modeling the soft clay, it was investigated the behavior of soft soil improved by stone columns. The ratio between the compression index (λ^*) and compression unloading index (κ^*) used in this study is equal (8.1) [10] .

Kahlstrom (2013) [3] investigated the behavior of primary consolidation of soft clay, it was compared the results of numerical analysis of finite elements using Plaxis 2D with theoretical and observed settlement. Two models are considered for simulation, Soft Soil model and Mohr-Coulomb material model .It can be concluded that for clay soils of heavy pre-consolidated pressure in case of a thin upper layer exposed to compression, the prediction of settlements using Soft Soil model gives more accurate results than Mohr-Coulomb model.

A numerical analysis using Plaxis finite element software performed by Ibrahim et al. (2014) [11], it was investigated the 2D simulation for the strip footing rested on soft clay to assess more accurate model to predict the behavior. Several tests were performed to get the chemical and physical properties of the clay. Two material models are used (Mohr-Coulomb and Soft Soil model). It was observed that the model of soft soil reveals more accurate results of settlements than the Mohr-Coulomb model.

Liong (2014) [12] investigated the better prediction of modeling Jakarta red clay using three types of constitutive models , Mohr-Coulomb, Hardening, and soft soil model. It was used to simulate the consolidated undrained Triaxial tests, from the results obtained it can be observed that the model of Soft Soil gives a stiffer stress-strain behavior compared to Hardening model.

Waheed and Asmael (2019) [13] investigated the analysis of the shallow foundation behavior rested on clay utilizing three constitutive finite elements models, Mohr-Coulomb, Hardening, and Soft Soil model. It was examined the response of loading of small and large size of footing. For the case of small scale, as can be seen in Figure (3), it can be noted that the analysis using the model of soft soil shows a stiffer response of the load-settlement behavior compared to other models, while for large foundation size, it shows reasonable results for simulation the shallow foundation behavior in clay.

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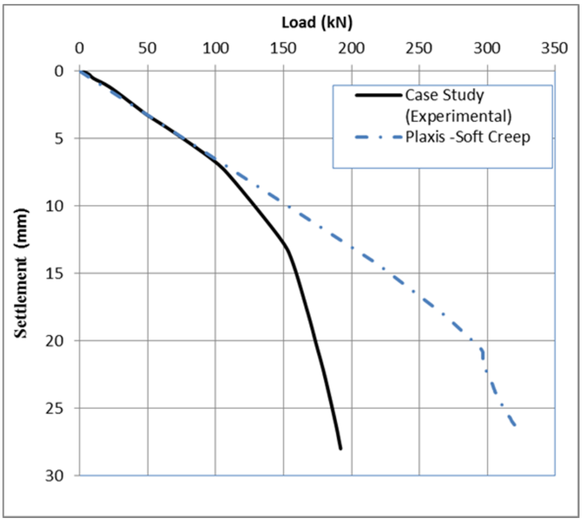

Fig. 3. The load-settlement relationship of small-size footing in clay using Soft Soil model.[13]

Ambassa and Amba (2020) [14] analyzed the experimental results of oedometer and triaxial compression tests performed on Cameroon clays to obtain the stiffness and parameters of shear strength considered in the model of Soft Soil, it can be noted that using this model for compressible clays needs a longer calculation time, as the stiffness matrix was included in each of calculation step. Moreover, the representation using Soft Soil model shows reasonable results of the behavior of a compressible clayey layer and it is possible to use it for modeling the geotechnical structures in this soil.

Al-Dawoodi et al. (2022) [15] examined the modeling using Soft Soil model of the load-settlement response of shallow footing exposed to a pressure of three cases of undrained cohesion (cu) of clayey soils, i.e (16, 25, and 70 kPa). The results show that for soft clay (cu=16) , there was a good agreement with experimental results, moreover for stiff clay it is underestimated in the final stages of loading.

Waheed and Asmael (2023) [16] performed an experimental and numerical analysis to assess the immediate settlement, and the settlement due to consolidation of shallow footings in clay of different cases. The results of the analysis are compared with the calculated settlement; the finite element analysis was performed using the model of Soft Soil. It was concluded that the analysis by Soft Soil constitutive model under-predicted the value of immediate settlement by about (30 %) and it shows a good agreement for consolidation settlement.

4 Conclusions

In this paper, according to the main finding of the previous studies regarding using the model of Soft Soil in numerical analysis in geotechnical engineering, it can be concluded:

1. In the model of Soft Soil, the yield surface coincides with modified model of Cam Clay with respect to the flow rule for strain in a plastic state, and the parameters of stiffness can be considered from the test of oedometer test.
2. The main advantage of the model of soft soil, the stiffness is dependent with stress in a logarithmic relationship., and this can distinguish between the loading and unloading state.

3. The main disadvantage of this model, it was suitable, especially, for normally consolidated clay in a soft case, and did not take into account the creep state.
4. The parameters considered in the soft soil model are equal to (12) parameters.
5. The ratio of the modified compression index (λ^*) to unloading /reloading index (κ^*) is from (5 to 10).
6. The Soft Soil model gives a stiffer stress-strain behavior compared to Hardening model.
7. The using of the model of Soft Soil for compressible layers of soil needs a longer calculation time than other models as the material stiffness matrix was included in each calculation step.
8. The model of soft soil shows better prediction in the analysis of both immediate in addition to consolidation settlement of foundation in clayey soil than the Mohr-Coulomb model.

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