

Evaluation of Sand Constitutive Models for Analysis of Piled Raft Foundation

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Abstract

Constitutive models play an important origin in the geotechnical problems design. In order to make the models useful to geotechnical engineers, some numerical predictions are presented to compare the performance of different models with experimental results (Full scale tests). It was found from this study that hardening soil model (HS small model) gave good prediction of settlement more than hardening model and Mohr-Coulomb model. Also, the errors in prediction of maximum settlement pile raft, pile group and raft are ranged (3-4) %, (6-7) % and (27-36) % for hardening soil with small strain model, hardening model and Mohr-Coulomb model respectively.

Keywords: Constitutive models, Numerical modeling, piled raft.

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Introduction

At last few decades, there has been an increase in recognition that the using of pile groups in concurrently with the raft can perform to noticeable economy without bargaining the performance and safety of the foundation. Likes a foundation that using both the piles and the raft is called as a pile- raft or a piled raft. Furthermore, the piled-raft concept has been evincing to be an economical procedure to improve the performance and serviceability of foundation by decreasing settlements to acceptable limits. In spite of the piled-raft concept has been most notably used to new construction such as high-rise buildings, it is also beneficial for moderate height structures and remedial works [1]. Piled raft foundations are compound structures different from classical foundation in which the load of structure is either transferred by the piles or the raft alone. In a piled raft foundation, the contribution of the raft in addition to the piles is taken into account. The piles transfer a part of the structure loads into stiffer layers and deeper of soil to allow the reduction of settlement and differential settlement in a very economical way. Piles are used up to a load level which can be of the same order of value

of the bearing capacity of single pile or even greater [3]. The adoption of piled raft foundations concept in the design of pile groups is by no namely new but has been described by several authors, including [4, 5, 6]. In the early period, the use of numerical methods was confined to simple problems because of the limited availability of computers memory and low processing speed. In the last two decades, because of the rapid development in computer programs, numerical methods such as full three- dimensional methods are usually used to solve complex problems. Though the (MC) model, (HS) model and (HS small) model have been implemented into some of the commonly used software, few of them in literature are studied in relative to field measurements. Hence, this study aims to evaluate the performance of those models. It is expected that the evaluation can be helpful to engineers and researchers to perform analysis using those models more confidently. Evaluation of the performance of the above mentioned models requires good case histories. Piled raft, pile group and raft foundation are one of good cases study that chosen in this study that have field monitoring data and data of soil testing were recorded well [9].

Constitutive Models

Soil is a multi-phase, non-linear and time-dependent material. Therefore; the soil model such as the essential relation between stress and strain, is very complex. A lot of equations that define the stress-strain relationships for a soil represent the constitutive relation. The essential relation may be modeled more or less accurate and with emphasis on different features. Plaxis has carried out different material models which suitable for different cases. The three selected models will be reviewed in this study.

1. Mohr-Coulomb (MC) Model

The (MC-model) is an elastic perfectly-plastic model. In general, the model is used as a first estimation of soil behavior. The model is isotropic and does not account for soils stress-dependency, i.e. soils tendency

to stiffen with increased pressure. It is recommended using this model in an initial estimation of soil because of a relatively fairly accurate and fast [8]. The MC model requires five parameters Young's modulus (E), Poisson's ratio (ν), friction angle (ϕ°), cohesion (C), and dilatancy angle (ψ°). Those parameters can be acquired from essential tests on soil samples.

2. Hardening soil (HS) Model

The HS model is a forerunner elastoplastic model used to simulate different kinds of soils, both soft and stiff soils [7]. It is stress dependent stiffness behavior according to a power law and hyperbolic stress strain relationship in axial compression. It is failure behavior according to MC criterion and plastic strain by primary compression. The background of this kind of models is the hyperbolic relationship between vertical strain and stress which have been obtained from standard triaxial tests. Such a criteria was first described by [10] and later used in the famous hyperbolic model [2]. On the contrary to an elastic perfectly plastic model like MC, the HS model has a yield surface not fixed and expands due to plastic strain, therefore: it describes the plasticity more realistic. In HS model, the soil is described much more accurately by using three different input stiffness's; these are triaxial loading secant stiffness (E_{50}), unloading/reloading triaxial stiffness (E_{ur}) and the oedometer loading stiffness (E_{oed}) [8].

3. Hardening soil with small strain (HS small)

This model is, as the name indicates, a version of the HS model. Hardening-soil model with small-strain stiffness (HS small-model) is a more advanced version, with focus on describing soil's behavior more accurately while unloading and reloading the soil. It is very stiff behavior at very small strains and may best for application such as excavations and tunnels. The original HS-model models the stress-strain relation in this phase as linear-elastic with the stiffness (E_{ur}). However, when a normally consolidated soil is unloaded and reloaded it will behave nonlinear and plastic. The HS small-model requires several parameters. The parameters can be obtained from basic tests on soil samples, these parameters with their standard units are listed below.

E_{50}^{ref} : Secant stiffness from triaxial test at reference pressure (kN/m^2).

E_{oed}^{ref} : Tangent stiffness from oedometer test at p pressure (kN/m^2).

E_{ur}^{ref} : Reference stiffness in unloading / reloading (kN/m^2).

Go Reference shear stiffness at small strains (HS small only) (kN/m^2). Shear strain at which G has reduced to 70% (HS small) (kN/m^2)

M: Rate of stress dependency in stiffness behavior.

p^{ref} : Reference pressure (100 kPa) (kN/m^2).

ν_{ur} : Poisson's ratio in unloading / reloading.

C' : Cohesion (kN/m^2).

Φ' : Friction angle (degree).

Ψ : Dilatancy angle (degree).

RF :Failure ratio q_f / q_a like in Duncan- Chang model (0.9).

Ko^{NC} : Stress ratio $\sigma'_{xx} / \sigma'_{yy}$ in 1D primary compression.

Case Study

The piled raft, pile group and raft foundation were chosen as a case study for this paper due to readily available documentation of construction procedure, full scale test and in situ conditions released by [9]. The profile of soil was obtained depend on the results of a geotechnical investigation including two boreholes and a standard penetration tests (SPT) within the area of the study. The soil profile consists of two main layers. The upper layer consists of very dense yellowish to brown sandy soil from (0 to -5 m) depth and the second layer consisting of medium dense light brown to brownish yellow sandy soil from (-5 m to -15m) depth. A full scale model for foundation of piled raft has been executed and tested in the Karbala soil. The raft and piles are made of concrete, while the soil was dry sand. The results of (2x2) piled raft foundation; Figure 1 depicts the layout of the piled-raft foundation considered in this analysis as a reference to check the numerical solution carried out by PLAXIS-3D program. The model sand ground was modeled during utilizing the (HS small)

model, HS model and MC model. The (HS small) model has the parameters listed in Table 1. The strength model parameters and the soil stiffness have limited effects when remaining within acceptable range. It is clear that the stiffer behavior was as a result from effect of driving of piles that increase soil horizontal stresses and lead to larger shear mobilization. This can be achieved in the model by increasing Koini. Ko could be increased to large values (2-3.5) along with increasing dilatancy angle to get good agreement with the experimental study. Figure 2 shows the quarter of the problem analyzed by PLAXIS-3D program. While Figure 3 depicts the mesh of the finite element of the vertical loading, taking into consideration the elastic behavior of concrete of the piled raft and the elastoplastic behavior of sandy soil by amalgamating the three models.

Table 1 Material properties of the sand adopted in the soil model in HS small and others models [9].

| Property | Very dense sand | Medium dense sand |
|---------------------------------|-----------------|-------------------|
| Unit weight(kN/m ³) | 20 | 20 |
| Drainage type | Drained | Drained |
| E50,ref(kPa) | 60000 | 35000 |
| Eoed,ref(kPa) | 60000 | 35000 |
| Eur,ref(kPa) | 180000 | 105000 |
| M | 0.4 | 0.5 |
| Vur | 0.15 | 0.15 |
| Pref(kPa) | 100 | 100 |
| $\gamma_{0.7}$ | 0.15E-4 | 0.15E-4 |
| G0,ref(kPa) | 130000 | 100000 |
| Cohesion C(kPa) | 0.10 | 0.10 |
| Friction angle(ϕ) | 41 | 35 |
| Dilatancy angle(ψ) | 11 | 5 |
| Tension cut off(kPa) | 0 | 0 |
| Konc=1-sin ϕ | 0.344 | 0.426 |
| Koini=Konc | 0.344 | 0.426 |

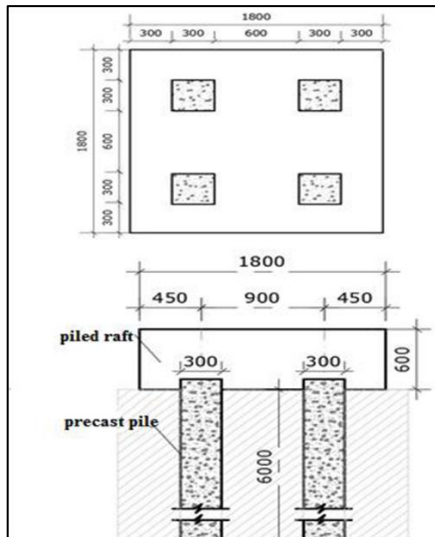


Figure 1: The problem of piled raft foundation (2x2) used for numerical modeling (all dimensions are in mm)

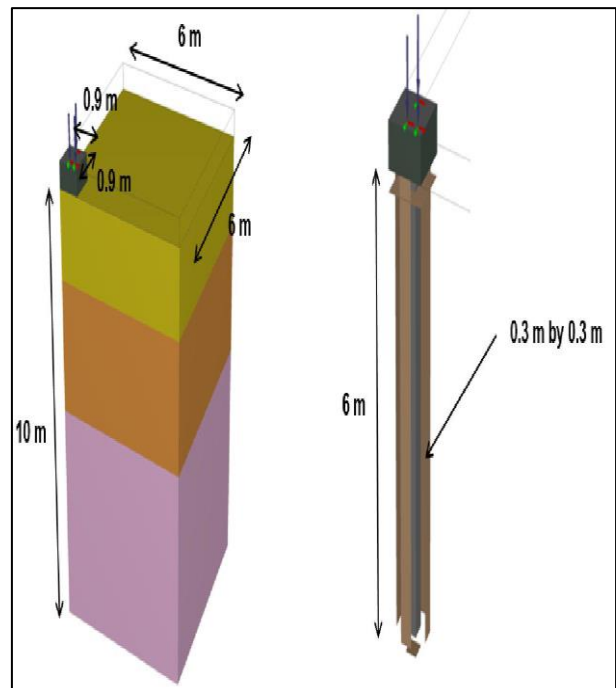


Figure 2: Quarter of the problem of piled raft (2x2) as executed by Plaxis-3D

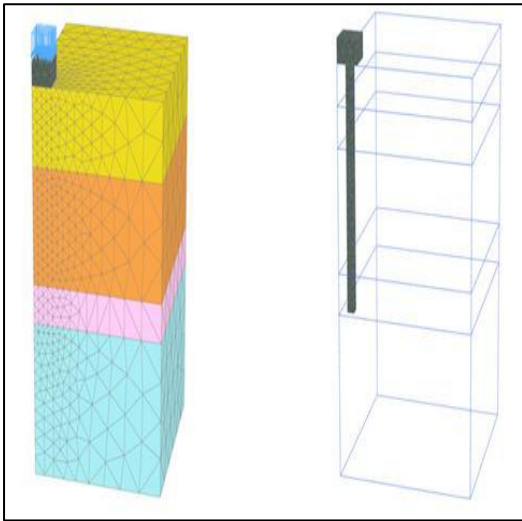


Figure 3: Mesh of the finite element of piled raft model for vertical loading

Results and Discussion:

The load settlement curves have been drawn for piled-raft, pile group and raft foundation as shown in Figures 4 to 6. The results of each case are discussed briefly as follows:

1. Piled-raft:

It can be seen from Figure 4 that the MC model overestimated the experimental results comparing with hardening model and hardening small model. The maximum settlement value predicted by this mode was approximately (29) mm in comparison to the maximum observed settlement of (21.3) mm. In contrast, the hardening and hardening small constitutive models provided good prediction of settlement of piled-raft and slightly underestimated the maximum settlement of piled-raft by (1.30)mm and (0.80)mm respectively. In the lower applied loads, the settlement of MC model is approximately converging to the experimental but begins to diverge in higher applied loads.

2. Pile-group:

It is clear from Figure 5 that the hardening and hardening small overestimated the settlement of experimental results. Mohr-Coulomb model overestimated the experimental results until reach applied load of (460) tons, beyond this load begins to underestimate and diverges from experimental results. The error in maximum settlement values predicted by hardening small, hardening and

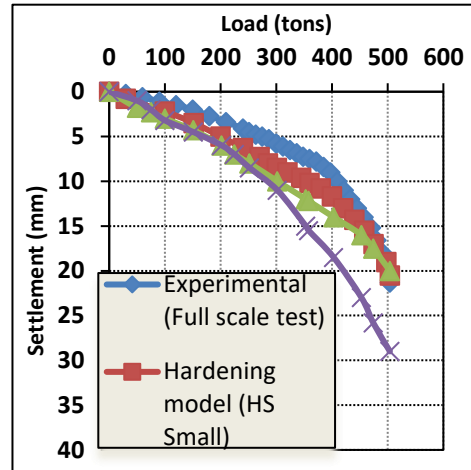


Figure 4: Load-settlement curves between experimental and numerical results of models for case of piled-raft

Mohr-Coulomb models are 3%, 7% and 27% respectively.

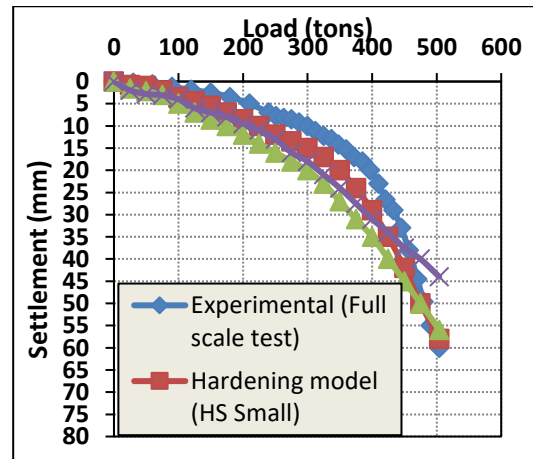


Figure 5: Load-settlement curves between experimental and numerical results of models for case of pile group

3. Raft:

Figure 6 shows the load settlement curves of experimental and three models for raft foundation. It is obvious from this figure that the behavior is approximately the same behavior of previous pile group case. The Mohr-Coulomb model overestimated the settlement until reach applied load of (200) tons, beyond this load, the settlement begins to underestimate and diverges from experimental results. The error in maximum settlement of raft are 3%, 7% and 29% for hardening small, hardening and Mohr-Coulomb models respectively. In general, the hardening small gave good agreement with

experimental results and more than other models hardening and MC. Despite the relatively few material parameters used in MC model, it retains an acceptable degree of first predictive capability for many problems. The MC model is assumed that the soil is elastic perfectly plastic that means the yield surface of the MC model is fixed. The hardening small and hardening models are nonlinear elasto-plastic behavior that introduces an additional volumetric cap of yield surface.

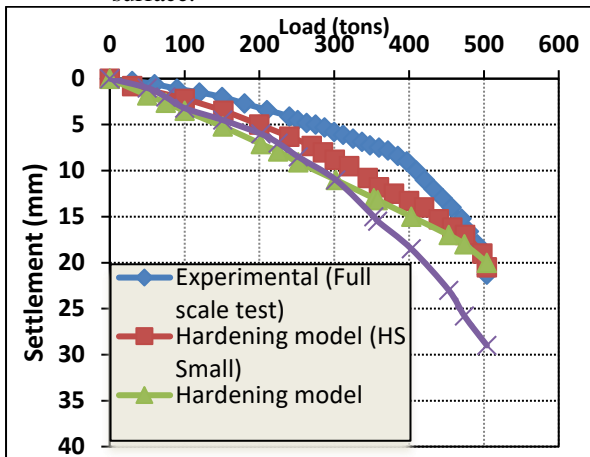


Figure (6): Load-settlement curves between experimental and numerical results of models for case of raft

Conclusion

1. The hardening small model gave a good prediction of settlement with experimental more than hardening and Mohr-Coulomb models.
2. The errors in prediction of maximum settlement are ranged (3-4) %, (6-7) % and (27-36) % for hardening small, hardening and Mohr-Coulomb models respectively.
3. Although the Mohr-Coulomb model needs little material parameters, it retains an acceptable as a first estimation of settlement for many problems.
4. The nature of problem (with pile or without pile) has effect on prediction of settlement curves for different constitutive models.

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