Effect of Mesh Size on Soil-Structure Interaction in Finite Element Analysis

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Abstract- Numerous constitutive models have been developed over the past years for modelling the stress-strain behaviour of soils, using finite element and/or finite difference calculations of soil structures and soil/structure interaction problems under axisymmetric, plane strain, and/or general three dimensional conditions. Selection of the appropriate parameters and soil model can have a significant impact on the results of numerical analysis. In this study, the interaction of soil and reinforced cement concrete raft foundation in a sandy soil at a depth of 9m below the existing ground level is analysed by using with both analytical and finite element analysis (FEM). Analytical calculations were done using method available in literature and a finite element analysis was carried out using the hardening soil model available in PLAXIS 2D (2020, connect version). The results obtained from analytical calculations were compared with those obtained from the Hardening Soil (HS) Model. In the model sizes of mesh were changed and there effect on interaction behaviour is observed by studying the strength and deformation results obtained from FEM analysis. It was observed that very fine mesh size gave more accurate results compared to the other sizes.

Keywords- Plaxis, sand, settlement, Raft

I. INTRODUCTION
Evaluation of correct strength and deformation behaviour of raft resting on the soil is important for safe and economical design. Strength and deformation behaviour of raft foundation can be analysed by different numerical methods. With the development of numerical methods such as finite element analysis and finite difference method, it has become feasible to analyse and predict the behaviour of complex soil structures and soil/structure interaction problems. Such analyses depend on the representation of the relations between stresses and strains in a given material and are represented by a constitutive model, consisting of mathematical expressions that model the behaviour of soil in a single element. Therefore the purpose of a constitutive model is to simulate the soil behaviour with sufficient accuracy under all conditions with sufficient accuracy under all loading conditions in the numerical computations.

II. LITERATURE REVIEW
The Hardening Soil model was established in 1999 [1]. In the framework of the theory of elasticity. The model involves friction hardening to model the plastic shear strain in deviatoric loading, and cap hardening to model the plastic volumetric strain in primary compression, because of these two types of hardening, the model is accurate for problems (like excavations) involving a reduction of mean effective stress and at the same time mobilization of shear strength. The verification and formulation of this model was discussed [1]. It is an advanced and latest model for the simulation and modelling of soil behaviour. The Hardening soil model requires the input of 10 parameters, i.e. three reference stiffness parameters ($E_{ref}^{s}$ for triaxial compression, $E_{ref}^{c}$ for triaxial unloading and $E_{ref}^{o}$ for oedometer loading) at a reference stress level $P_{ref}$, a power, $m$, for the stress dependent stiffness formulation, poisson’s ratio for unloading and reloading, $\mu$, the mohr coulomb strength parameters, $\phi$, and $\gamma$, the K0 value in primary one-dimensional compression ($K_{o}$), a parameter called the failure ratio, $R_f$ which determines the strain level at failure [2]. Fig. 1 shows the failure criterion of the hardening soil model in principal stress space. The yield surface of the hardening soil model is not fixed in principal stress space, but it can expand due to plastic straining. The Plaxis hardening model can be used to accurately predict displacement and failure for general types of soils in various geotechnical applications [3]. The model does not include anisotropic stress or stiffness, nor time-dependent behaviour (creep). The hardening soil model is also known for stress-dependency of stiffness moduli [4]. This explains that all stiffnesses increases with the pressure.

Figure 1: Failure criterion of the Hardening soil model in principal stress space [1].

The Hardening Soil model, also called as HS-Standard was explained by [1]. In order to modify the important phenomena which is exhibited by soils such as:

1. Densification, defines as decrease of the voids volume in soil due to plastic deformations, which also decreases the void ratio,
2. Stress-dependent stiffness, is basically an observed technique of increasing the stiffness modules with the increasing of confining stress,
3. Soil stress history, explains the accounting for preconsolidation process and its effects,
4. Plastic yielding, is very important which accounts for the development of irreversible strains with reaching a yield criteria,
5. Dilatancy, explains as the uses for an occurrence of negative volumetric strains during shearing.

This model is known to be one of the simplest and important in the class of latest models designed to handle the small strain stiffness as explained by [5]. It has two plastic mechanisms, shear and volumetric. Different to the other material models such as the Cap model or the Modified Cam Clay model, the magnitude of soil deformations, stresses, forces, etc. can be modelled more accurately by using three different input stiffness parameters which is related to triaxial loading stiffness (E_50), triaxial unloading-reloading stiffness (E_un), and oedometer loading modulus (E_ood).

There are five parameters in the hardening soil model differ than the MC model is:
1. (E_50) secant modulus 50% strength[kN/m²]
2. (E_ood) Oedometric modulus [kN/m²]
3. (E_un) Unloading-reloading modulus[kN/m²]
4. (v_un) Unloading-reloading Poisson’s ratio [-]
5. (m) Exponent of the stress-stiffness function

Parameters previously used in MC model:
1. (Ø) Friction angle ['°]
2. (c) Cohesion [kN/m²]
3. (ψ) Dilatancy angle ['°]

The hardening model can be used to predict displacement and failure for different types of soils in various geotechnical applications. This model does not include anisotropic strength or stiffness, nor time-dependent behaviour (creep). Its capabilities for dynamic applications are limited, but this model is, in principle, without any doubt the most accurate general soil model.

A. Correlation between Angle of Friction and Standard Penetration Number

The peak friction angle Ø’, of granular soil has also been correlated with N_60 by several investigators. A correlation between N_60 and Ø’ was given by [6] in a graphical form, which can be approximated as,

\[ \theta'(deg) = 27.1 + 0.3N_{60} - 0.00054[N_{60}]^2 \]  

B. Correlation between Modulus of Elasticity and Standard Penetration Number

The modulus of elasticity of granular soils (E_s) is an important parameter in estimating the elastic settlement of foundations. A first order estimation for E_s was given by [7] as

\[ \frac{E_s}{p_u} \propto N_{60} \]  

Where

\[ \alpha = 5 \] for sands with fines
10 for clean normally consolidated sands
15 for clean overconsolidated sands

\[ p_u = \text{atmospheric pressure in the same units as } E_s \]
\[ N_{60} = \text{Field standard penetration number} \]

III. PROBLEM STATEMENT

Bearing capacity requirement is a basic criteria to be satisfied in the analysis and design of shallow foundations. The criterion on bearing capacity ensures that the foundation does not undergo shear failure under loading. The use of standard penetration test in the analysis of bearing capacity has received numerous attentions [8]. Details of the field application of Standard Penetration Test are specified in IS 2131 [9]. This paper attempts to report interaction behavior of raft foundations resting on sand using Finite element software package provided by Plaxis 2D (connect edition). Steps for modeling is presented in fig. 2 from the model definition to the output results

IV. SELECTION OF PARAMETERS

Parameters used in this study were obtained through laboratory investigation of the undisturbed samples collected from site located at Noida in India, as most of the strata is having poorly graded sand, collection of undisturbed sample was difficult. Hence, the result of standard penetration test conducted as per IS 2131 [9] is used for analysis. Table 1 summarizes the selection of model parameters for analysis of the hardening soil model used in this study.

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Step 1:
- Define the model
- Input geometry + Structural element
- Apply boundary conditions

Step 2:
- Apply loading
- Add material properties
- Mesh generation
- Create construction stages
- Input anchor supports to retain the excavated earth

Step 3:
- Initial flow and boundary condition
- Generation of initial pore water pressures

Step 4:
- Calculation of results

Step 5:
- Deformed mesh and displacement diagrams
- Output results

Figure 2: Steps for numerical modeling

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SOIL PROFILE AND BOREHOLE DETAILS

The samples were collected from two bore holes drilled at GH-01A/01, SECTOR-16, GREATER NOIDA WEST, U.P (India) and tested as per the relevant protocol of bureau of Indian Standard. The results of SPT are presented in Table 2.

ANALYTICAL METHOD

The analytical calculations were done in accordance with Indian standards IS 6403 [10] and permissible settlement is restricted as per IS 1904 [11].

Based on the shear criterion IS code 6403 [10], net ultimate bearing capacity for local shear failure for a cohesionless sand

\[ q_{nu} = q(N_q - 1) + \frac{1}{2} By N_q s_y d_y i_q w' + \frac{1}{2} B\gamma N_q s_y d_y i_q w'' \]

Where \( s_q, s_y = \) shape factors \\
\( d_q, d_y = \) depth factors \\
\( i_q, i_y = \) Inclination factors

\( N_q, N_y = \) Bearing capacity factors

\( w', w'' = \) Correction factor for location of water table.

Assuming there will be rise in water table during monsoon and water will reach to a level of bottom of raft.

\[ \theta' = tan^{-1}(0.67\tan\theta) = 22.78^\circ \]

\[ N_q=8.76, N_y=8.44 \]

Assuming a factor of safety of 2.5, net safe bearing capacity( \( q_{ns} = \) )

\[ = 883.95 \text{KN/m}^2 \]

| TABLE 1: SELECTION OF MODEL PARAMETERS FOR ANALYSIS USING THE HARDENING SOIL MODEL |
|----------------------------------------|---------|---------|---------|
| General                               | Model   | Hardening soil model | - |
| Material model                        | Type    | Drained           | - |
| Type of material behaviour            |         |                   |   |
| Soil unit weight above phreatic level | \( \gamma_{un} \) | 16.20 (lab) | KN/m² |
| Soil unit weight below phreatic level  | \( \gamma_{s} \) | 19.10 (lab) | KN/m² |
| Parameters                            |         |                   |   |
| Young’s modulus                       | \( E' \) | - | KN/m² |
| Secant stiffness in standard drained triaxial test | \( E_{so} \) | 3.0x10⁴ (Plaxis) | KN/m² |
| Tangent stiffness for primary oedometer loading | \( E_{tan} \) | 3.0x10⁴ (Plaxis) | KN/m² |
| Unloading/reloading stiffness          | \( E_{ur} \) | 1.00x10⁵ (Plaxis) | KN/m² |
| Power for stress-level dependency of stiffness | \( m \) | 0.5 (Plaxis) | - |
| Cohesion (constant)                   | \( C \) | 0 (lab) | KN/m² |
| Friction angle                        | \( \phi \) | 32 (lab) | - |
| Dilatancy angle                       | \( \psi \) | 2.0 (lab) | - |
| Poisson’s ratio                       | \( \mu \) | 0.2 (lab) | - |
| K₀-value for normal consolidation     | \( K_0 \) | 0.4701 (Plaxis) | - |
| Interfaces                            |         |                   |   |
| Strength reduction factor Int.        | \( R_{max} \) | 0.67 (plaxis) | - |
| Initial                               |         |                   |   |
| K₀ determination                      |         | Automatic | - |
| Over-consolidation ratio              | OCR    | 1.0 (plaxis) | - |
### TABLE 2: SPT VALUES FOR DIFFERENT BOREHOLES

| Depth (m) | Field N-Value | Corrected N-value | Field N-Value | Corrected N-value |
|-----------|---------------|-------------------|---------------|-------------------|
| 1.5       | 10            | 17                | 7             | 12                |
| 3         | 12            | 17                | 9             | 13                |
| 4.5       | 18            | 21                | 13            | 15                |
| 6         | 20            | 20                | 17            | 17                |
| 7.5       | 24            | 22                | 19            | 17                |
| 9         | 25            | 21                | 24            | 20                |
| 10.5      | 26            | 20                | 27            | 21                |
| 12        | 34            | 24                | 29            | 21                |
| 13.5      | 37            | 25                | 30            | 18                |
| 15        | 39            | 20                | 34            | 19                |
| 18        | 44            | 21                | 39            | 20                |
| 21        | 51            | 22                | 46            | 21                |
| 24        | 56            | 23                | 52            | 22                |
| 27        | 58            | 23                | 54            | 22                |
| 30        | 59            | 23                | 59            | 23                |
| 33        | 55            | 21                | 62            | 23                |
| 36        | 60            | 22                | 66            | 23                |
| 39        | 68            | 23                | 71            | 24                |
| 42        | 70            | 23                | 76            | 25                |
| 45        | 75            | 24                | 81            | 25                |

### TABLE 3: PARAMETER USED FOR CALCULATION BY ANALYTICAL METHOD

| Bore hole No | 1 & 2 | Unit | Protocol |
|--------------|-------|------|----------|
| Depth of water table | 14 | m    |          |
| density above water table | 16.2 | KN/m^3 |          |
| density below water table | 19.1 | KN/m^3 |          |
| Type of foundation | raft |      |          |
| width of foundation | 40 | m    |          |
| length of foundation | 42 | m    |          |
| depth of foundation | 9 | m    |          |
| Permissible settlement of foundation | 0.075 | m |          |
| Cohesion (c) | 0 | kN/m^3 | Direct Shear Test | |
| Angle of internal friction (φ) | 32 | Degree |          | |

Bearing capacity based on the settlement criterion

\[
N_{cor} = 22
\]

\[
\gamma_d = 16.2 KN/m^2
\]

\[
\gamma_{sat} = 19.1 KN/m^2
\]

\[
\mu = 0.2
\]

\[
C = 0
\]

\[
\Theta = 32^\circ
\]

\[
S_e = \frac{q_n B (1 - \mu^2) I_F}{E_s}
\]

(4)

Where \(q_n\) = Net safe bearing pressure

\(B\) = breadth of foundation

\(E_s\) = Young’s modulus

\(I_F\) = Influence factor

\(s_c\) = allowable settlement (75mm)

V. NUMERICAL ANALYSIS

Plaxis 2D was used to evaluate the performance of the Hardening Soil model to estimate the bearing capacity of a raft foundation situated at a depth of 9m below the surface and to investigate the relationship between the results obtained. Fig 3 shows a sketch of the prototype dimensions showing the location of the water table. Simulations for different excavation stages were done. The distance between the boundary of the floor of the model and the lower boundary of the footing plays an important role in the pattern of bearing capacity value obtained.

![Figure 3: Prototype dimensions](image-url)

![Figure 4: Load-settlement relationship for the Hardening soil model](image-url)

75mm allowable settlement, from equation 4, \(q_n\) = 456.7KN/m². Therefore, considering the lower of the two values obtained, Allowable bearing capacity of the foundation was obtained as 456.7KN/m².
To eliminate the effect of this factor, the bottom line intended at a distance greater than 2d.

It can be seen from fig 4, that Plaxis 2D software provides a linear load-settlement relationship for the hardening soil model, which is variant from the theoretical load-settlement curve for a foundation on sandy soil. The curve also indicates an initial negative settlement indicating a swelling in the soil before the footing is placed and load is applied. The reason for initial negative settlement is due to release of in situ soil pressure due to excavation.

VI. EFFECT OF CHANGES OF MESH SIZE ON THE BEARING CAPACITY OF FOUNDATION

Here, the effect of mesh size changes on the model output results was analysed. Different mesh sizes were used in Plaxis 2D which are: very coarse, coarse, medium, fine and very fine. It should be noted that the mesh size of 15 nodal element is a better distribution of nodes and more accurate results than to element with six nodes. Therefore, the analysis of 15 nodal element is used. Table 3 shows the effect of changes of mesh size on settlement pressure of foundation for 75mm settlement. Figure 7 shows the effect of change in mesh size on deformation of a raft foundation.

TABLE 3: EFFECT OF CHANGE IN MESH SIZE ON ALLOWABLE BEARING CAPACITY OF FOUNDATION

| Allowable bearing capacity of foundation at 75mm settlement (KN/m²) | Change in type of mesh size |
|---|---|
| 484 | Very coarse |
| 488 | Coarse |
| 480 | Medium |
| 465 | Fine |
| 460 | Very fine |

From Fig 7, it can be seen that there is slightly or no difference in the pressure for 75mm of settlement. But at settlement more than 75 mm the effect of mesh size is to decrease the settlement for a given pressure if mesh size is increased from very fine to very coarse.

VII. CONCLUSION

Based on the findings, the following conclusions can be drawn;

1. The bearing pressure for a given settlement obtained by the hardening soil model was closer to the IS analytical method. However an initial settlement of 20mm should be deducted to cater for the swelling provided by plaxis FEM, because of removal of insitu stress because of excavation.

2. Mesh size with 15 nodal elements produces more accurate results as compared with element with six nodes.

3. The mesh sizes influences the bearing pressure for a given settlement. The influences are negligible at a settlement value of 75mm, but influences increase with increase in settlement.

4. Bearing capacity value increases with increase in refinement of mesh size in Finite element analysis. When a finer mesh is used, the value of bearing capacity obtained at a particular settlement is higher than that obtained when a coarse mesh is used. This therefore means researchers should ensure that a fine mesh is used when carrying out finite element analysis to obtain more accurate results.
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