Bearing Capacity Analysis of Piled Raft Foundation by Numerical Analysis Using Finite Element Method (FEM) for Dhaka-Chittagong Elevated Expressway

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Abstract

Bearing capacity is one of the most important characteristics of any kind of soil. For every construction work it is compulsory to calculate the bearing capacity of soil of study area for particular type of foundation. Bearing capacity is generally calculated by some conventional equations like Terzaghi's bearing capacity equation and Meyerhof's bearing capacity equation and for different types footings these equations vary. In this research extended sub-loading tij model for Finite Element Method (FEM) is used to calculate the bearing capacity of piled raft foundation. Elasto-plastic constitutive model parameter identification is an important task for proper modeling of any soil. In this research, subsoil characteristics of study locations are presented based on field and laboratory test results. Elasto-plastic constitutive model parameters of study locations soil has been determined for extended sub-loading tij model. In this study some soil parameters are determined from laboratory tests and by using these, simulation parameters like Compression index for FEM tij simulation (λ), Swelling index for FEM tij simulation (Ḱ), Critical stress ration (RCs) and Void ratio at 98KPa (N) are calculated. Using these parameters, bearing capacity of piled raft foundation has been estimated for 0.05% settlement of soil section. Considering the effect of settlement in 2D Finite Element analysis have been conducted. It is found that bearing capacity determined by the conventional methods match well with the results of the numerical simulations.

Keywords: Constitutive Model, Bearing Capacity, Settlement, Finite Element Method etc.

1. INTRODUCTION

Bearing capacity is estimated by limit analysis using upper bound and lower bound theory. But the limit state analysis cannot consider the effect of Over Consolidation Ratio (OCR), bonding effect of soil. Therefore, in estimation of bearing capacity such parameters should be considered. A now-a-days FE method is widely used in different fields of Geotechnical Engineering. So, such condition can also be applied for bearing capacity estimation. However, the accuracy of the FE analysis depends on the constitutive models of soils. Available constitutive models such as Camclay model (Roscoe and Burland, 1968), Drucker-Prager Model, Mohr-Coloumb Model cannot properly consider or explain soil behavior of different densities. However, in this paper extended sub-loading *tij* model (Nakai and Hinokio, 2004; Nakai et al., 2011) is used which can consider influence of intermediate principal stress on the deformation and strength of soils, dependence of the direction of plastic flow on the stress paths, influence of density and/or confining pressure and bonding effect on the deformation and strength of soils (Shahin et al,. 2004; Nakai et al., 2010; Nakai et al., 2011).

Pile foundation is a popular deep foundation type used to transfer superstructure load into subsoil and bearing layers. However, accurate prediction of piles' settlement is particularly difficult concerning complicated consolidation process and pile-soil interaction (Kazimierz, 2015). Piles are commonly used to transfer superstructure load into subsoil and a stiff bearing layer. As it was emphasized by

Lambe and Whitman (1969), a pile foundation, even in the case of single pile, is statically indeterminate to a very high degree.

The present study is limited to sub-soil properties parameters for constitutive modeling of the ground where the proposed Dhaka-Chittagong elevated Expressway will be constructed. The main objectives of the study are:

1. Determination of elasto-plastic constitutive model parameters for extended sub-loading *tij* model.
2. Determination of load bearing capacity of piled raft foundation.

2. METHODOLOGY

2.1. Study Area

For the soil investigation, we have selected several places in Narayanganj and Comilla districts. In Narayanganj, we have collected soil from Sonargaon (23°38′51″N to 90°35′52″E with an area of 171.02 km^2) and Bandar (23°37′N to 90°31.5′E with an area of 55.84 km^2) upazila. In Comilla, we have collected soil from Comilla SadarDakshin (23°22′N to 91°12′E with an area of 241.66 km^2) and Chouddagram (23°13′N to 91°19′E with an area of 268.48 km^2) upazila, (BBS 2011).

2.2. Material Collection

Soil samples are collected as boring sample using Shellby tubes. Hence, the samples were undisturbed. The length of each tube was 450 mm. we have collected samples from different depths of earth i.e. 2m, 5m, 10m, 20m and 30m below from the earth surface. These samples are then tested in laboratory by different experimental procedures.

2.3. Laboratory Experiments

Undisturbed samples were collected during field investigation from the selected study areas. Laboratory tests were conducted according to ASTM standards (ASTM, 1989). Index and strength properties were determined to evaluate the sub-soil condition of study area. Moisture content test, specific gravity test, atterberg limit test, consolidation test and unconfined compression test of soil were conducted at four selected sites.

3. INDEX PROPERTIES OF SOIL

Index properties of the clay layer have been presented in Table 1. Specific gravity of the clay layer varies in the range 2.68 to 2.71. Dry unit weight of the soil varies between 14.11 and 16.20 kN/m^3. Natural moisture content of the soil varies in the range 23.0 and 40.0. Liquid limit and plastic limit of the clay layer vary in the range 48 and 56, 21 and 28, respectively. Sand, silt and clay content of the layer are 3~10%, 49~70% and 27~41%, respectively.

Table 1. Index properties of soil

Soil Parameters	Narayanganj		Comilla	
	Sonargaon	Bandar	Sadar Dakshin	Chouddagram
Specific Gravity, G_s	2.70~2.71	2.67~2.68	2.68~2.69	2.66~2.68
Dry unit weight, γ_d (KN/m^3)	15.79~16.20	14.65~14.96	15.07~15.86	14.11~15.02
Natural moisture content (%)	23.0~23.2	24.5~26.7	23.7~26.0	26.0~40.0
Liquid Limit, LL (%)	49~50	52~53	48~50	45~56
Plastic Limit, PL (%)	18~22	24~25	21~22	25~28
Unconfined compressive strength, q_u (KPa)	110~139	112~119	89~134	62~64

4. PARAMETER IDENTIFICATION FOR CONSTITUTIVE MODELING

4.1. Some Important Features of Sub-loading t_{ij} Model

An elastoplastic constitutive model for soils, called the extended subloading t_{ij}-model (Nakai, 2011), is used in the finite element analysis. This model, despite the use of a small number of material parameters, can describe properly the following typical features of soil behaviors (Nakai and Hinokio, 2004 & Nakai, 2011):

(i) Influence of intermediate principal stress on the deformation and strength of geomaterials.
(ii) Dependence of the direction of plastic flow on the stress paths.
(iii) Influence of density and/or confining pressure on the deformation and strength of geomaterials.
(iv) The behavior of structured soils such as naturally deposited soils.

A brief description of the above mentioned features of this model can be made as follows:

Influence of intermediate principal stress is considered by defining yield function f with modified stress t_{ij} (i.e.,defining the yield function with the stress invariants(t_N and t_S) instead of (p and q). The yield function is written as a function of the mean stress t_N and stress ratio $X \equiv t_S/t_N$ based on t_{ij} by Equation 1.

$$f = \ln\frac{t_N}{t_{N0}} + \varsigma(X) - \left(\ln\frac{t_{N1e}}{t_{N0}} - \ln\frac{t_{N1e}}{t_{N1}}\right) = 0 \tag{1}$$

Here, t_{N1} determines the size of the yield surface (the value of t_N at X=0), t_{N0} is the value of t_N at reference state and t_{N1e} is the mean stress t_N equivalent to the present plastic volumetric strain which is related to the plastic volumetric strain ε_v^p as

$$\varepsilon_v^p = \frac{\lambda-\kappa}{1+e_0}\ln\left(\frac{t_{N1e}}{t_{N1}}\right) \tag{2}$$

The symbols λ and κ denote compression index and swelling index, respectively, and e_0 is the void ratio at reference state. In this research, the expression for $\varsigma(X)$ is assumed as,

$$\varsigma(X) = \frac{1}{\beta}\left(\frac{X}{M^*}\right)^{\beta} \tag{3}$$

The value of M* in Equation 4. is expressed as follows using principal stress ratio $X_{CS}\equiv(t_S/t_N)_{CS}$ and plastic strain increment ratio $Y_{CS}\equiv(d\varepsilon_{SMP}{}^{*p}/d\gamma_{SMP}{}^{*p})_{CS}$ at critical state:

$$M^* = \left(X_{CS} + X_{CS}{}^{\beta-1}Y_{CS}\right)^{1/\beta} \tag{4}$$

and these ratios X_{CS} and Y_{CS} are represented by the principal stress ratio at critical state in triaxial compression R_{CS}.

In elastoplastic theory, total strain increment consists of elastic and plastic strain increments as,

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p \tag{5}$$

Here, plastic strain increment is divided into component $d\varepsilon_{ij}{}^{p(AF)}$, which satisfies associate flow rule in the space of modified stress t_{ij}, and isotropic compression component $d\varepsilon_{ij}{}^{p(IC)}$as given in Equation 6.

$$d\varepsilon_{ij}^p = d\varepsilon_{ij}^{p(AF)} + d\varepsilon_{ij}^{p(IC)} \tag{6}$$

The components of strain increment are expressed as,

$$d\varepsilon_{ij}^{p(AF)} = \Lambda\frac{\partial f}{\partial t_{ij}} \quad and \quad d\varepsilon_{ij}^{p(IC)} = K\langle dt_N\rangle\frac{\delta_{ij}}{3} \tag{7}$$

Here, Λ is the proportionality constant, δ_{ij} is Kronecker's delta and <> denotes Macauley bracket. Dividing plastic strain increment into two components as in Equations 6 and 7 for the same yield function, this model can take into consideration feature (ii), i.e., the dependence of the direction of plastic flow on the stress paths, (Mohammad et al., 2013). Adding the term $G(\rho)$ in the denominator of the proportionality constant Λ of normal consolidated condition, influence of density is considered. The proportionality constant Λ is expressed as,

$$\Lambda = \frac{\dfrac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij}}{\dfrac{1+e_0}{\lambda-\kappa}\left(\dfrac{\partial f}{\partial t_{kk}} + \dfrac{G(\rho)}{t_N} + \dfrac{Q(\omega)}{t_N}\right)} = \frac{df_\sigma}{h^p} \tag{8}$$

$$K = \frac{1}{\dfrac{1+e_0}{\lambda-\kappa}\left(1+\dfrac{G(\rho)}{a_{kk}}\right)} \cdot \frac{1}{t_{N1}} \tag{9}$$

In feature (iv), the stress-strain behavior of structured soil can be described by considering not only the effect of density described above but also the effect of bonding. Two state variables ρ related to density and ω representing the bonding effect are used to consider feature (iv). The following relationships for $G(\rho)$ and $Q(\omega)$ are adopted in the model:

$$G(\rho) = sign(\rho)a\rho^2 \quad and\ Q(\omega) = b\omega \tag{10}$$

Where a and b are material parameters.

The parameters of subloading t_{ij} model are fundamentally the same as those of the Cam clay model (Roscoe and Burland, 1968), except for the parameter a, which is responsible for the influence of the density and the confining pressure. Parameter β controls the shape of the yield surface. The performance of the constitutive model has already been checked in numerical simulations (Shahin et al. 2004; Shahin et al., 2011; Nakai et al., 2010).

4.2. Layers of Soil Section with Piled Raft Foundation

Figure 1. is a section of piled raft foundation with different layers of soil.

4.3. Mesh of Soil Section

Figure 2. is the mesh with dimension of the same section which has been done for simulation work.

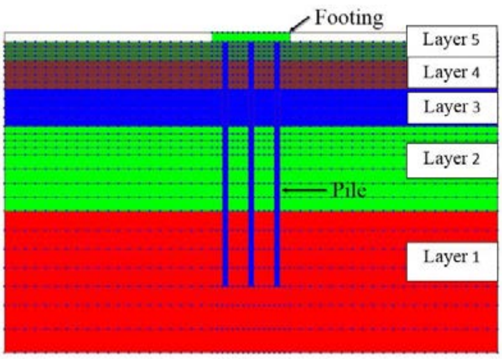

Figure 1. Layers of piled raft foundation soil section

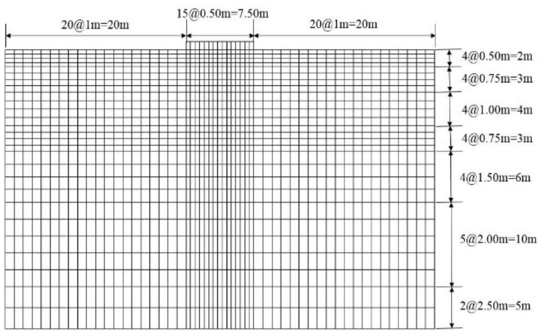

Figure 2. Finite Element Mesh for piled raft foundation

4.4. Determination of Soil Parameters

For getting parameters of the constitutive model (Table 2), consolidation tests for study locations have been carried out in laboratory. Figure 3 shows the relations between void ratios and mean effective stress in logarithmic scale. From these curves, compression index λ, swelling index $\acute{K}$ and void ratio at

98kPa, N are obtained for both soils by using Equations 11, 12 and 13. Using these values and fitting the computed curve parameter *a* (density parameter) of sub-loading t_{ij} model is obtained.

λ = 0.434 × Cc (11)

Ḱ = 0.434 × Cs (12)

N = Void ratio at 98 KPa (13)

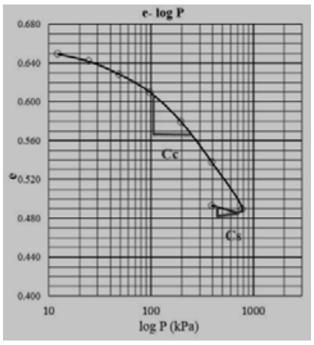

Figure 3. Calculation of C_c and C_s from e vs. logP curve

Table 2. Simulation parameters

Soil Layers	Depth (m)	λ	Ḱ	β	RCs	N	e0	aAF	aIC
1	0.00-2.00	0.07	0.0045	2	3.2	1.1	0.8	30	30
2	2.01-5.00	0.1038	0.00829	1.6	3.98	0.865	0.879	800	800
3	5.01-9.00	0.1018	0.00803	1.6	4	0.868	0.88	850	850
4	9.01-18.00	0.0819	0.00983	1.6	4	0.778	0.789	800	800
5	18.01-33.00	0.0879	0.00894	1.6	4	0.602	0.62	800	800

5. RESULTS AND DISCUSSIONS

5.1. Initial Stress Distribution of the Ground

Figure 4. shows the initial distribution of stress without piled raft foundation. Here, the stress in the deepest layer is the highest.

5.2. Stress Distribution of the Ground with Structure Load

Figure 5. shows the initial distribution of stress with piled raft foundation. Here, it is shown how the piles are distributing the loads in the soil layer.

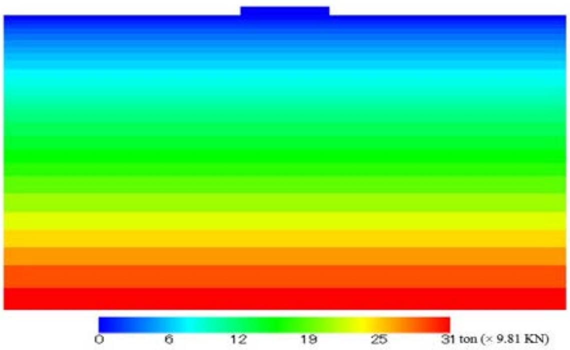

Figure 4. Stress distribution without piled raft foundation

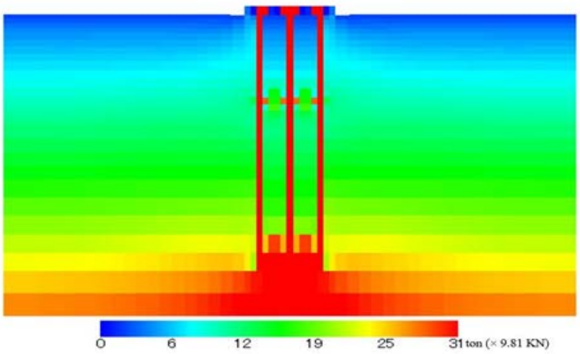

Figure 5. Stress distribution with piled raft foundation

5.3. Load-Displacement Relation

This the final result of our study through simulation. Figure 6. shows the load bearing capacity of soil. For 0.05% settlement the soil can take 880 ton load.

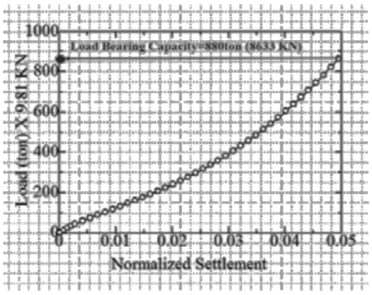

Figure 6. Load vs. Settlement curve

6. CONCLUSIONS

This paper determines soil parameters for Dhaka-Chittagong Elevated Expressway. This involved study area selection, soil sample collection, laboratory experiments, numerical analysis, calculation of simulation parameters and simulation by using Finite Element Method (FEM). It is concluded that load bearing capacity for 0.05% vertical settlement of soil is 8633 KN.

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