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Evaluating the Effect of Embedment Depth on Collapse Failure Analysis of Strip Foundation

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Abstract Bearing ultimate capacity of shallow footing on uniform soil can be evaluated experimentally. However, analytical and experimental methods are difficult to analyze and predict complicated behaviour of soil beneath the footing collapse failure on layered soil. A strip footing on dense sand overlying soft clay of bearing capacity is computed utilizing the three-dimensional (3D) geometry model by finite element method analysis. The soil model of the Mohr-Coulomb failure criterion is selected in the assessment. The effect of embedment depth with ratio foundation width (B) to the top layer thickness (H) exposed to vertical point loading is evaluated for different strength properties of soil layers. The present results were verified from established analytical formula. It shows the ultimate bearing capacity on layered soils on a strip footing increase in width of the footing. Local shear failure mechanism is observed in one of all cases with most cases indicate general shear failure mechanism occur for layered soil of dense overlying soft clay.

Keywords Embedment Depth, Ultimate Bearing Capacity, Layered Soils, Collapse Failure

1. Introduction

Strip footing is one of a shallow foundation types which fail due to a decrease in bearing capacity and rise in settlement when designing geotechnical structural applications, such as wall foundations, offshore platforms, and machinery foundations. It is utilized to give steady or straight superstructure loading which transfers the loading from the superstructure to the soil underneath. Shallow footings are placed on a soil layer of limited thickness extend beyond a thick stratum of another soil which may be either one bedrock or different strength of soil layer.

Factors need to be considered while designing the foundations, such as component of soil weight, shear strength parameters (mechanical characteristic) and depth, width and shape of footing (physical characteristics) on a horizontal ground surface [1].

In designing a safe foundation, the bearing capacity of the footing is a main criterion to investigate by geotechnical engineers. The maximum founding depth of a strip footing is 3 m from the ground surface. The bearing capacity analysis of strip footing underneath the structure must satisfy design criteria of bearing capacity analysis which is safety against failure, adequate depth and tolerable settlement [2].

The maximum stress is which soil can carry without undergoing a shear failure in defining the ultimate bearing capacity of foundation. Based on the shear strength parameters of the soil, Terzaghi [6] was the first to calculate the ultimate bearing capacity of a strip footing resting on a uniform horizontal ground, which is used extensively even today. The modified of Terzaghi's theory in bearing capacity has shown changes on the bearing capacity factors with inclusion of several new factors [4-5,9, 26].

There are many factors contributing to the surface failure of ultimate load in the soil changes due to the soil layer's shear strength physical characteristics such as depth of upper layer, footing shape and size as well as embedment depth, a ratio of the upper layer thickness to a width of footing. Bearing capacity failure of a strip footing overlies on single layer or multiple layers is different in design and analysis due to factors and assumptions made in identifying a problem and solution.

If a footing is placed on stratified soils and the thickness of the top stratum form the base, H is less than the depth of penetration $H_{critical} = 0.5B \tan (45+ \varphi/ 2)$ the rupture zone extends to the lower layers depending on theirs thickness and needs modification on ultimate bearing capacity equation [7]. There are three cases available for stratified soils when i) footing on layered clays ($\varphi = 0$) (top layer stronger than bottom layer and vice versa, ii) footing on cohesive-frictional soils, iii) footing on sand-clay layer soils and vice versa.

In the past years, the analysis of the collapse shear failures of a strip footing over a two layers foundation clay were analyzed experimentally [8]. Study approaches on bearing capacity of shallow footings on layers soil has been studied extensively are covered analytically [9], semi-empirical [10], empirical to finite element methods [11-12]. The ultimate bearing capacity of the layered soil chose finite element analysis [11-12] for handling complex layered pattern and complex behaviour of soil for examples [13] examined plane-strain footings on sand overlaying clay soils and [14] calculated the undrained soil on two-layered clays. Besides [15] studied a square footing rested on the ground surface of two-layered clay soils. From previous studies show that analysis statements were made on the general shear failure process occur with small penetration before achieving the ultimate load. Doubtful to happen where a hard layer overlays a soft layer, a punching shear failure with large penetration happens.

The three-dimensional (3D) strip footing model on dense sand overlying soft clay failure analysis was utilized to examine the collapse failure of the footing under static vertical loading of 500 kN/m^2 required. The finite element method (FEM) results of bearing capacity analysis by the ratio of footing width to the top layer thickness (B/H) and size of footing width effects of layered soil have been evaluated and the results of which have been compared with the existing equations.

2. Collapse Failure Analysis

The bearing stratum of the stratified soils is weaker or stronger for layers soil than basic layer which has different strength characteristics.

If the footing laid on thin stiff layer over a soft deposit, it may punch through the top layer into the underlying stratum in which resulted settlement and ultimate bearing capacity will extent to large and governed by strength characteristics of the underlying stratum and vice versa when a footing resting on thick soft layer overlying a stiff layer, the ultimate bearing capacity will be limited to the upper layer of the soil. The collapse failure of the stratified soil is controlled by the thickness of the upper layer and the strength characteristics of the two layers of the soils [7, 16].

A strip footing placing on a dense sand that spread over the surface a soft clay shows that the bearing capacity is increased with sand-layer thickness until about $H_1/B \geq$: 2.5; thereafter, it remained constant at a value equal to the ultimate bearing capacity of an infinitely thick dense sand layer. In another condition of a strip footing placing on a dense sand layer that overlies a strong clay, the test results showed a decrease in the ultimate bearing capacity with increasing sand-layer thickness. The bearing capacity decreases from the initial maximum value (for a footing on an infinite clay layer) to the minimum for a footing on a thick sand deposit.

For standard bearing capacity pressure, q_u of Terzaghi [6] when there is no presence of frictional property of soil and overburden pressure in the ground can be expressed in Equation 1. In order to evaluate the average limit pressure (p_u) as defined by the following expression:

$$p_u \quad \frac{Q_u}{\pi b^2} \tag{1}$$

Here Q_u is the magnitude of the collapse load. The value of $p_u/(\gamma b)$ becomes a function of the following non-dimensional parameters as expressed in Equation 2:

$$p_u/(\gamma b) = f\,(H/B,\ c_u/(\gamma b),\ q/(\gamma b),\ \varphi) \tag{2}$$

Where φ defines the friction angle of the sand layer and c_u denotes the undrained shear strength of the clay.

A punching shear failure, semiempirical attempts have been recommended based on experimental findings by [9-10, 17] which also called punching shear models, since the sand layer is in a state of passive failure along vertical planes below the edges of the footing. The punching shear coefficient, Ks varies on the angle of internal friction of the sand layer [18] mobilized angle of friction (δ), the undrained shear strength of the clay (c_u), the angle of friction of the sand (φ), and the bearing capacity ratio (q_1 / q_2) based on Equation 3 proposed by Burd [13] to estimate ultimate bearing capacity of a strip foundation in the event of a punching shear failure [10] as expressed below:

$$q_u = cNc+\gamma H^2(1+(2D/H))K_s\tan \varphi/B+\gamma D \tag{3}$$

For the internal friction angle φ of 35° and the width of footing B varies between 1 to 3 metre, the punching shear coefficient, K_s in the range of 2.85 – 1.96.

A failure structure of footing on dense sand superimposing soft clay shows the possibility for ‘punch-through’ failure exists [19-20] due to a rapid decline in bearing resistance when the footing hits a block of sand into the underlying soft clay in an uncontrolled manner.

For a circular footing lying on dense sand soft clay layer, the collapse magnitude was generated by [10] o as below:

$$p_u/(\gamma b) = p_{u\text{-}clay}/(\gamma b)+(h/b)^2\ sk_s \tan\varphi-(h/b)\leq p_{u\text{-}sand}/(\gamma b) \quad (4)$$

where $p_{u\text{-}clay}$ and $p_{u\text{-}sand}$ are the bearing capacities for a circular footing placed over a homogeneous clay and sand, s is shape factor and k_s is the punching shear coefficient.

Collapse failure were studied by [7, 21] on two-layer soils. A dense sand overlying soft clay show the yield patterns of local shear failure limited to sand layer were observed leads to a wider spread of the plastic zone. It also leads to an extensive increase in the bearing capacity with optimum thickness (h_{opt}) of the sand layer always exist further increase in the bearing capacity occurs with an increase in H/B by considering the sand strata alone below the footing [21].

3. Materials and Methods

This study involves with identification index properties and engineering properties of the clay and sand for an input parameter in analytical analysis and numerical modelling. Finite element model with three-dimensional (3D) geometry model was drawn, input parameters were assigned, and later boundary conditions were applied. A static vertical loading was assigned on foundation until collapse failure took place. The simulation and analysis in numerical modelling were incorporated in geotechnical finite element program PLAXIS v.8. Later, finite element analysis results were verified from [9-10].

3.1. Experimental Work

Soil samples were collected from a construction site in Seberang Jaya, Pulau Pinang by an open excavation between 0 and 7m from ground surface. Approximately around 10kg of soil sample was collected and brought back to the laboratory for further testing. Sample was chosen from one location and soil types for all samples were taken at the same location.

From the visual observation during the soil sample collection, the marine soil was greyish in colour along with some fragments of shell similar with results reported in [22]. The greyish colour may be developed from the sulphur and iron oxidation process in the clay as a result of being exposed to the environment and contained organic matters.

Fig. 1 shows the location of the soil collection samples were conducted which is in front of the Sunway Carnival Mall, a shopping mall at Seberang Jaya, Pulau Pinang.

The tests were performed on a locally available marine clay in Seberang Perai, which is fine-grained. The moisture content, particle size distribution test determination and the Atterberg's limit test were applied according to BS 1377: Part 2:1990 [22]. The pyknometer bottle technique was performed the determination of the specific gravity of the marine clay samples. The dry-sieving technique is adopted to determine the particle size distribution; if the percentage soils at the last pan were greater than 10%, the experiment continued with the hydrometer test.

The Atterberg limit test or known as the consistency index tests were liquid limit and plastic limit conducted to classify soft clay plasticity index. The cone penetration tests were conducted to determine liquid limit by using cone penetration test at 20 mm penetration. By rolling the soil thread into a 3 mm diameter without crumbling the plasticity limit was determined. The plasticity of soil can be determined by using the Plasticity Chart. Moreover, compaction testing for 3kg of soil sample passing 37.5 mm sieve was prepared and 7% of water by soil weight were added to the soil sample.

Standard proctor of 2.5 kg as known, BS light was use to obtained compaction characteristics of marine soil. The sample was compacted in three equal layers using a rammer where each layer experienced 27 blows that were evenly distributed over the mould area. From the compaction curve, the maximum dry density, ρd_{max}, and optimum moisture content, w_{opt} were achieved. The laboratory work was conducted based on BS 1377: Part 4: 1990.

Table 1 lists index and engineering properties of the clay and sand soils. The shear box tests on dry samples of the sand prepared with the applied normal stress in the range of 50–150 kPa gave the angle of shearing resistance, ϕ, of 35°. Triaxial compression tests for the same range of normal stress and relative density under unconsolidated undrained conditions gave the cohesion of 20kPa. The index and engineering properties of marine clay soil as shown in Table 1.

Figure 1. Location of soil sampling

Table 1. Index and Engineering Properties of Marine Soil

Properties	Present Study	[22]
Specific gravity, Gs	2.48	2.27
Sand (%)	-	41.05
Silt (%)	-	50.37
Clay (%)	-	8.44
Plastic limit, PL (%)	36.67	32.00
Liquid limit, LL (%)	68.37	68.00
Plasticity index, PI (%)	31.70	36.00
Optimum Moisture Content, OMC (%)	20.24	16.34
Maximum Dry Density, MDD (Mg/m^3)	1.568	1.64
Classification of soil from Atterberg limit test	CH	CH
Cohesion, c, kN/m^2	20	-
Friction angle, φ°	35	

3.2. Numerical Modelling of Soil

Finite element method incorporated in geotechnical software PLAXIS 3D was used to numerically model the collapse failure of footing. The finite element program is very great tool to predict complex behavior of stress-strain soil [25]. The finite element 3-D analysis has been carried out to study the collapse load of a shallow strip footing lying on a dry dense sand overlies soft clay. The aim of this study is to analyze the collapse load of the strip foundation by under the same loading for the difference ratio of width footing to the top layer thickness, B/H.

3.2.1. Geometry Model of Soil

A strip foundation of width B is placed on dense sand layer which overlies on soft clayey layer strata. The depth of the sand layer is H. The total layered of soil is 4B. The footing is placed on ground surface with embedment depth of 0.5 meter and it is subjected to vertical downward load (Q) without any eccentricity. Loading of 500 kN/m^2 required up until failure is attained. The soil layers are assumed to be perfectly plastic and obey non-associated flow rule of the Mohr-Coulomb failure criterion.

By adopting the 3D incremental stress-strain analysis geometry model, a plane stain strip footing was counted as inflexible, and the footing was built on the inserted at various depth from the ground surface in the top strong soil layer. From the ground surface, 4B was set at the vertical boundary side. Fig. 2 is the model geometry of the problem adopted in the numerical study.

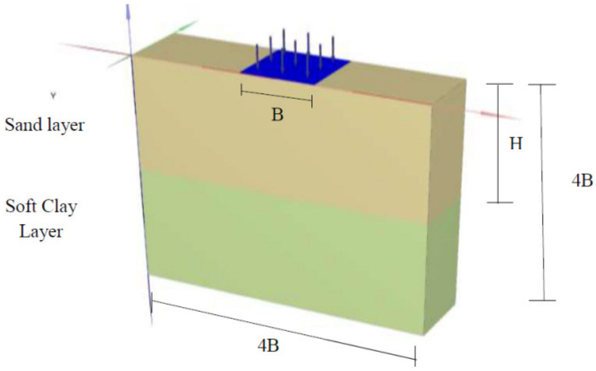

Figure 2. Geometry model of the layered soil

To estimate the bearing capacity of footing in the numerical framework, various footing width of a strip footing have been chosen for the numerical analyses. Table 2 shows the parameters for strip footing that were used in finite element analysis. The depth of footing was 0.5 m. Besides, the sizes of foundation were 1m, 2m and 3m. The total of layered soil was 4B and the top layer thickness was label as H.

Table 2. Footing Parameters

Parameter	Value
Footing Depth, D_f	0.5 m
Footing Width, B	1m, 2m, and 3m
Footing Length, L	4B
Top layer height, H	H
Total height of layered soil, H_{total}	4B

3.2.2. Load and Boundary Conditions of Soil

500 kN/m^2 vertical loading was imposed until failure attained. From the ground surface, 4B was set as the vertical boundary. The stress induced terminated at this depth as assumed at early stage of analysis. The mesh will vary as the size footing B is increase as well as the model size.

In the numerical model, ‘‘standard fixity’’ condition has been employed. Horizontal fixity was applied to the lateral vertical edges, while the bottom edge of the model was fixed and assumed to be non-yielding [1] and restrained from both vertical and horizontal movements. The upper surface of the model was kept free while on all vertical surfaces, roller supports were provided.

3.2.3. Material Model of Footing and Soil Parameters

A finite element program of PLAXIS 3D was employed and elastic perfectly plastic soil failure criterion of Mohr-Coulomb was selected to assess failure analysis of the footing dense overlying soft clay which failed in a linear elastic. The Mohr–Coulomb model involves the following six input parameters: unit weight, γ; Young’s modulus, E; Poisson’s ratio, ν; cohesion, c; angle of internal friction, φ; and dilatancy angle, ψ. The footing width has affected on the top layer thickness ratio (B/H) and width of foundation were analyzed with a unit weight of sand and clay were 20 kN/m^3 and 18 kN/m^3 respectively. The soil layers Poisson’s ratio was set to ν equal to 0.30 while the ratio of the elastic modulus was taken as E = 20 MPa. The value of internal friction angle for dense sand and undrained cohesion of soft clay was 35° and 20 kN/m^2 which were found experimentally from direct shear test and unconsolidated undrained respectively.

Table 3 shows a set of physical input parameters designated in the finite element analysis. The undrained B method was used as drainage type for the clay in the PLAXIS program. This kind of drainage was chosen for undrained behaviour or short-term material behaviour in which stiffness is defined in terms of effective properties and strength is defined as undrained shear strength.

Table 3. Dense Sand Overlying Soft Clay Input Parameters

Parameter	Sand	Clay	Footing
Material Model	Mohr-Coulomb	Mohr-Coulomb	Linear elastic
Type of material behaviour	Drained	Undrained (B)	Non-porous
Soil unit weight, γ_{unsat}, kN/m^3	18	17	-
Soil unit weight, γ_{sat}, kN/m^3	20	18	-
Young’s modulus, E, kN/m^2	2 x 10^4	3 x 10^4	1 x 10^{12}
Poisson’s ratio, ν	0.3	0.3	0.15
Cohesion, c, kN/m^2	0.2	20	-
Friction angle, φ	35	-	-

3.2.4. Mesh Generation and Sensitivity

Fig. 3 shows fine mesh configuration was assigned near the area below of strip footing. The medium mesh was used for the rest of layered soil to avoid time-consuming while analyzing in the finite element program.

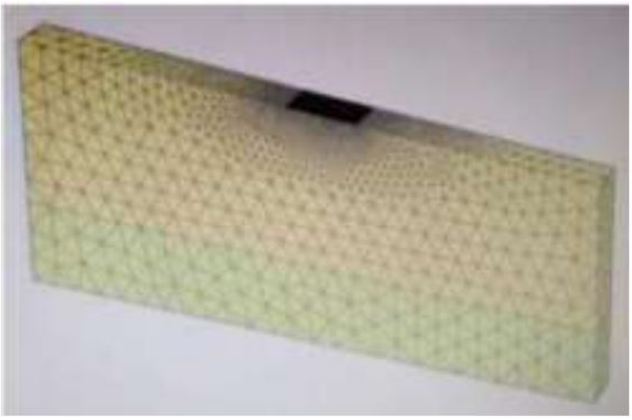

Figure 3. Typical mesh geometry model

Three-node triangular elements are used to discretize the problem domain. To simulate a sudden change in the directions of the principal stresses at the edge of the footing, sizes of the elements are gradually decreased and approach the footing edge. Typical meshes for two different values of h/b, corresponding to φ = 35° and c = 20 kPa, are illustrated in Fig. 3, respectively [21].

between numerical and semi-empirical approaches compared to B = 2 and 3 m. The B = 2 and 3 m of strip foundation width can cater to the loading of 500 kPa. Most B sizes show percentage differences for both methods of analysis were below 20%. It should be observed that the present analysis provides slightly lower magnitudes of qu. The analytical analyses were carried out from [9-10] based on the limit equilibrium approach (LE) with an assumption of the geometry of the failure mechanism. Meanwhile for present study, the finite element method incorporated in the programming which brough to different results. The estimation of collapse load also affected the bearing analysis due to values of shear strength of the soils and the material model chosen in the finite element analysis method. The present analysis did not take into account the effect of stress level and flow rule on friction angle of sand layer could bring to underestimation of collapse loads.

Figure 6. Comparisons of q_u and B/H with different methods of analysis

Figure 7. Comparisons of q_u and B with different effect of embedment depth ratio

The failure process of strip footing in two layers of soil using shear strain curves in form of shadings and contour line was examined. The failure mode of damaged shear contour is observed in total incremental movements obtained from FEM. The failure mechanisms of three different size of footing are shown in Fig. 8 for B/H = 0.5, 1.0, 1.5 and 2.0. The red line marked the boundary between the upper and bottom soil layer. The squeeze collapse mode of dense sand overlying clay soils was observed. It is found that the depth of the failure mechanism decreases as the ratio of B/H increases as reported to [23]. Based on the results, general shear failure was observed for dense sand overlying soft clay in most of the cases. Overall shear failure occurs as the layer of soft clay acts as a fairly rigid foundation. However, local shear failure became obvious in the case of B/H = 0.5 and B = 2 m. The soft layer of clay is relatively weaker than the thick layer of sand. Therefore, it can be determined that the type of failure mechanism of layered soil depends on the thickness and width of footing.

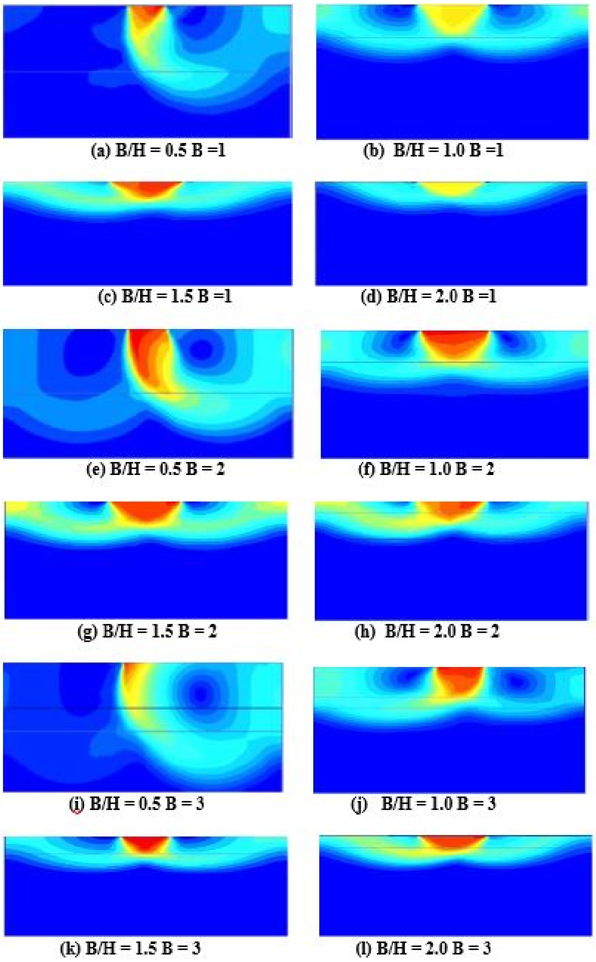
(a) B/H = 0.5 B =1 (b) B/H = 1.0 B =1
(c) B/H = 1.5 B =1 (d) B/H = 2.0 B =1
(e) B/H = 0.5 B = 2 (f) B/H = 1.0 B = 2
(g) B/H = 1.5 B = 2 (h) B/H = 2.0 B = 2
(i) B/H = 0.5 B = 3 (j) B/H = 1.0 B = 3
(k) B/H = 1.5 B = 3 (l) B/H = 2.0 B = 3

Figure 8. Comparisons of q_u and B/H with different methods of analysis [23]

Fig. 9 shows the shear strain contours at failure in form of contour line for B/H = 2.0. From this figure, it is observed that the depth of the contour line of B = 2 was deeper compared to B = 1. As the footing size increases, the contour line produced will improve too. It can be concluded that the depth of the failure zone increases when the size of the footing increase. Hence, footing width is one of the contributing factors affect the failure mode.

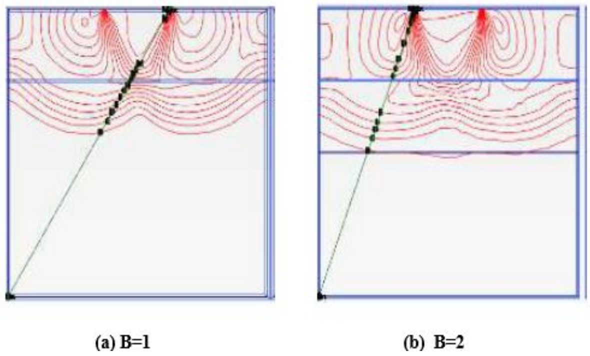

Figure 9. Contour line for ratio B/H = 2.0

5. Conclusions

The ultimate bearing capacity of strip footing on two layers of dense sand overlying soft clay has been investigated by using the finite element and analytical method. The effect of embedment depth (B/H) on bearing capacity was evaluated for different footing width. The ultimate bearing capacity of dense sand overlying soft clay decreases as the sand thickness ratio, B/H increases. The yield patterns have been observed for a dense sand overlying soft clay indicates a general shear failure of the layered soils. The thickness of the top layer and the strength properties of the two soil layers have influence on the ultimate bearing capacity.

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