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# Experimental Study of the Bearing Capacity of Footings on Stiff Clay Overlying Very Loose Sand

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## ABSTRACT

Experimental model tests were carried out to study the bearing capacity of footings on stiff clay overlying very loose sand. Emphasis was given to the effects of the thickness of the clay (H) relative to the footing size (D). The clay thickness was fixed during the experiments and the foundation was represented by rigid circular steel plates of different sizes to give H/D ratios ranging from 0.6 to 2.0. The shear parameters of the two soils were measured in the laboratory at their placement conditions. The load tests were carried out to failure. The load settlement curves showed non-linear relationship. The ultimate bearing capacity decreased with increasing plate diameter. For the same plate (150mm) the bearing capacity on homogeneous stiff clay is more than twice that of the stiff clay overlying loose sand. The bearing capacity factor Nc was back-calculated from the results of the model tests. The very loose sand caused the factor to decrease to values less than 3.0 for H/D smaller than 1.0. The effective depth which is the smallest thickness of the stiff clay that does not allow the lower layer to affect bearing capacity is greater than twice the plate diameter (> 2D).

## المستخلص

تم عمل نموذج عملي من اجل دراسة سعة التحمل للاساسات المتوضعه على طبقه طينيه صلبه والتي بدورها تتوضع على رمل مفكك وتاكد من خلال ذلك انه يوجد تاثير لسماكة الطبقه الطينيه الصلبه عندما تكون صغيره مقارنه بعرض الاساس على سعة التحمل.

سماكة الطبقه الطينيه كانت ثابته خلال جميع التجارب وتم استخدام اقراص دائرية من الحديد الصلب لتمثل الاساسات لها اقطار مختلفة بحيث تعطي قيم H/D تبداء من 0.6 الى 2.0 ومعاملات القص حددت كم خلال التجارب العلمية على العينات.

يستمر اجراء كل تجربة الى ان يحصل الانهيار، تُظهر منحنيات الاجهاد والهبوط علاقة غير خطية.

سعة التحمل في التربة المتجانسة لاعماق كبيرة تساوي اكثر من ضعفي سعة التحمل لنفس ابعاد الاساس في حالة التربة الطينيه الصلبه واسفل منها رمل مفكك.

معامل سعة التحمل $N_c$ تم حسابة باستخدام سعة التحمل المتحصل عليها من التجارب في النموذج ولوحظ انخفاضه الى اقل من 3 عندما تكون H/D اقل من 1. العمق الفعال والذي يُعَرف بانه اقل سماكه للطبقة الطينية الصلبة والذي عنده لايكون للرمل المفكك اي تاثير في سعة التحمل يكون اكبر من ضعفي قطر الاساس (2D).

**Keyword:** Bearing capacity, clay, sand, footings, overlying

## 1. Introduction

Soils are often deposited in layers. Within each layer the soil can be assumed as homogeneous. If a foundation is placed on the surface of a layered soil for which the thickness of the top layer is large compared to the width of the foundation, then realistic estimates of the bearing capacity may be obtained using conventional bearing capacity theories. However, this approach is not appropriate if the thickness of the top layer is small compared to the width of the footing. In recent years approximate solutions for the bearing capacity of shallow foundations on layered soil have been presented for a number of commonly encountered non-homogeneous soil profiles. Two cases of layered soil profiles have been generally considered, a strong layer overlying a weak one and vice versa.

The case of stiff to very stiff or hard clay overlying loose or medium dense sand is very common in Khartoum city. Pad footing and raft foundations are placed on the stiff clay and the influence of loading often reaches the underlying loose sand. The bearing capacity is estimated based on some generalized theoretical developments.

Experimental model tests for footings on layered soils with and without reinforcement were carried out by different researchers to study the different parameters and factors affecting bearing capacity (Das 1988; Oda and Win

1990; Abou Farah 2004; Hanna, 1981). The cases normally studied are dense sand or gravelly sand over loose sand or soft clay.

This is an experimental study investigating the case of rigid foundation placed on stiff clay overlying very loose sand. A physical model is used to investigate the effects of variation of the thickness of the stiff clay on the ultimate bearing capacity of the foundation system.

## 2. Ultimate Bearing Capacity of Layered Soils

Traditional bearing capacity theories for determination of the ultimate bearing capacity of shallow foundations assume that the thickness of the soil under footing is homogenous and infinite. The methods used for estimating the bearing capacity of multi-layered soils range from simply averaging the strength parameters (Bowles, 1988) to using limit equilibrium considerations (Meyerhof and Hanna, 1978) or more rigorous limit analysis approach (Michalowski and Shi, 1995) and using the Finite Element method for handling complex layered patterns (Burd and Frydman, 1997). Semi empirical approaches based on experimental studies (Brown and Meyerhof, 1969; Meyerhof and Hanna, 1978; Button, 1953) and experimental approaches from full field tests had been attempted for estimating the ultimate bearing capacity (Verma, 2013).

### 2.1 Theoretical Methods

Many theoretical and numerical methods have been proposed by different investigators to study the bearing capacity of footings on layered soils (Zhu and Michalowski 2005; Yamaguchi and Terashi 1973; Al-Shenawy and Al-Karni 2003; Burd and Frydman 1996; Michalowski and Shi 1995). The rigid plastic analyses for the bearing capacity problem for multi-layered soil were studied by Yamaguchi and Terashi (1973). The top and bottom soils were sand layers whereas the intermediate layer was soft clay. When the thickness of clay layer is relatively small compression failure is likely to occur, whereas in the case of clay layer of comparatively large thickness a splitting failure may be expected. Bearing capacity factors for each mode of failure were presented. The capacity is influenced by the angle of shearing resistance of clay and the ratio of the thickness of the clay layer to the width of the pressure zone on the surface of the clay layer.

Meyerhof and Hanna (1978) investigated the ultimate bearing capacity of a footing resting on two layered soil for the case of a dense or stiff layer overlaying a weak deposit. The analyses of different models of soil failure were compared with the results of model tests on circular and strip footing on layered sand and clay soils. Test results showed that the influence of the soil layers beneath the footing depends mainly on the shear strength parameters and bearing capacity ratio of the two layers. The shape, depth of the foundation and the inclination of the load had significant effect on the bearing capacity value. Failure mechanism was developed and punching shear failure occurred in the top (strong) layer and a general shear failure was generated in the bottom (weak) layer. They developed an equation to calculate the ultimate bearing capacity from the measured soil properties and the dimensions of the foundations. The equation for the ultimate bearing capacity ($q_u$) for the case of circular or rectangular foundation is given by:

$$q_u = q_b + \left[1 + \frac{B}{L}\right]\left[\frac{2c_aH}{B}\right]\lambda_a + \left[1 + \frac{B}{L}\right]\gamma_1 H^2\left[1 + \frac{2D_f}{H}\right]\left[\frac{k_s \tan\emptyset_1}{B}\right]\lambda_{cs1} - \gamma_1 H \le q_t \quad (1)$$

where :

$q_t$ is the ultimate bearing capacity of the top soil

$$q_b = C_2 N_{c2}\lambda_{cs2} + \gamma_1(D_f + H)N_{q2}\lambda_{qs2} + \frac{1}{2}\gamma_2 B N_{\gamma 2}\lambda_{\gamma s2} \quad (2)$$

$\lambda_{cs2,}\lambda_{qs2,}\lambda_{\gamma s2}$ are the shape factors for the top soil layer with friction angle $\emptyset_2$.

$$N_c = \cot\emptyset\left(N_q - 1\right)$$

$\lambda_{cs1,}$ is the shape factor related to coheγsion for the top soil layer

λa is a shape factor

$D_f$ is the depth of the footing in the soil

L and B are the footing dimensions

Georgiadis and Michalopoulos (1985) presented a numerical method for evaluating the bearing capacity of shallow foundations on layered soil, which may contain any combination of cohesive and non-cohesive layers. Several potential failure surfaces were analyzed and the minimum parameters of the soil for which the foundation is stable were determined.

Zhu (2004) and Michalowski (2005) investigated the case of strong clay, with thickness H overlying weak clay layer supporting strip and pad footings by using the ABAQUS program. It was stated that the presence of a weaker layer of clay below a stronger layer reduced the bearing capacity value. For the case when the top layer is weaker than the bottom layer, the bearing capacity factor $N_c$ decreases as H/B increases (B is the width of the footing) whereas for the case when the top layer is stronger than the bottom layerthe value of $N_c$ increases with increasing H/B value.

## 2.2 Experimental Methods

Das (1988) conducted a number of laboratory model tests to predict the ultimate bearing capacity of strip footings resting on two soil layers (sand layer on top of a weak clay layer) with and without the inclusion of geotextile at the interface of the two layers. The role of the geotextile was to improve the ultimate bearing capacity and settlement conditions of shallow foundations on soft clay soil and to reduce the thickness of the sand layer required to distribute the load. The experimental results showed an increase in the bearing capacity and reduction of the depth of the sand layer to be placed over the clay layer.

Oda and Win (1990) carried out an experimental work on a footing resting on a sand layer overlying a clay layer in order to study the influence of the soil layering on the ultimate bearing capacity of footings. Twelve tests were carried out on sand beds with an interstratified clay layer. For this purpose, the thickness and the depth of the clay layer were varied. It was found that the clay layer reduces the bearing capacity of the footing even at a depth five times greater than the width of the footing. Also it was proved that the presence of a thin clay layer even at a great depth reduces the bearing capacity of footings resting on granular soil.

Abou Farah (2004) investigated the ultimate bearing capacity of shallow foundations subjected to axial vertical loads and resting on soil consisting of two layers of strong cohesionless soil overlying weak deposit. A bearing capacity equation was derived as a function of the properties of the upper and lower soil layers, the thickness of the upper layer, the footing depth/width ratio and the angle of the failure surfaces with respect to the vertical load. For the case of dense sand layer overlying loose sand deposit the predicted values of the bearing capacity showed good agreement with the experimental results found by Hanna (1981).

The most common method for evaluation of ultimate bearing capacity from load test data of footings on soils are 0.1B method, the tangent intersection method and the log-log method (Michael, 1998). Details about these methods are given in the mentioned reference.

## 3.0 The Experimental Program and Set-up

### 3.1 The Program

Laboratory model tests were conducted to determine the ultimate bearing capacity of footings resting on layered soil system, namely stiff clay overlying very loose sand. The test was performed in a circular tank divided into two parts an upper part and a lower part. The two parts were designed in such a way that the upper part can be placed and fixed on the lower one. The sand was placed in the lower part whereas the clay was compacted in the upper part and then transported and fixed over the lower part with perfect contact between the two soils. Circular rigid steel plates (15 mm thick) having different sizes were used to represent the footings. A jacking system was used to apply the loads against a reaction frame, whereas a load cell and displacement transducers were used to record the load and settlements, respectively.

The experimental study included the effects of the thickness of the clay layer directly under the plate relative to the steel plate diameter on the bearing capacity of the foundation system.

### 3.2 Used Soils

Clay and sand soils were used. The clay was classified as low-plastic clay (CL). The sand used in this study is fine grained (maximum size 0.4 mm) and was obtained from the Nile river bed in Tuti Island at the confluence of the White Nile and Blue Nile in Khartoum. It was classified as silty sand(SM).The engineering properties of the sand and clay soils used in the experimental study are summarized in **Table 1**.

**Table 1: Properties of the clay and sand used in the experimental study**

| Properties | Clay | Sand |
|---|---|---|
| **Liquid limit** | 39 | N.L |
| **Plastic limit** | 25 | N.P |
| **Fines Content %** | 94 | 23 |
| **Specific gravity** | 2.72 | 2.74 |
| **Maximum density(g/cm$^3$)** | - | 1.659 |
| **Minimum density(g/cm$^3$)** | - | 1.358 |
| **Relative density $D_r$ (%)** | - | 14 |
| **Optimum moisture content (%)** | 27 | - |
| **Maximum dry density (g/cm$^3$)** | 1.47 | - |
| **Angle of internal friction ($\emptyset^{\circ}$)** | 20 | 30 |
| **Cohesion (kN/m$^2$)** | 88 | 3.5 |
| **USCS Classification** | CL | SM |

### 3.3 Set-up of the Experiment

The tank used in this study is 600 mm in diameter and 750mm in height. It is divided into two parts, the upper movable part and the lower fixed part with heights 150mm and 600 mm, respectively. The tank is made of 2.8 mm thick steel plate and strengthened with steel bars every150 mm. The upper and lower parts are fastened with steel bolts around the tank perimeter. The upper part of the tank is used to prepare the clay whereas the lower part is used for placing the loose sand. The loading frame consists of a reaction steel beam fixed to two steel columns founded on a concrete foundation. The steel beam and the steel columns are made of I-section 200mm height and 100 mm width. The load is applied at the center of the steel plates by a hydraulic jack connected to the reaction beam. The plate sizes are 75mm, 100mm, 150mm, 200mm and 250mm and the plate thickness is 15mm. A 5.0 tons capacity load cell is used to measure the applied loads and displacement transducers are used to measure the settlement. Data logger with eight channels read and records the loads and settlements every second. The Data logger is fully managed by the software built in it, via a sequence of menu displayed on the screen. **Fig. 1** shows the setup of the experiment and its instrumentations.

**Fig. 1: The set-up of the experiment**

### 3.4 Preparation of Soils

The natural moisture content was determined for the clay soil. Calculated amount of water was added to the dry clay and thoroughly mixed with it to achieve its Proctor optimum moisture content. The moist clay was placed in plastic bag for 24 hours to obtain a homogeneous product. The upper tank was placed on a leveled steel plate. The moist clay was manually compacted in the upper tank in five compacted layers; for each layer the maximum dry density was achieved. The upper half, filled with compacted clay, was weighed to find its density. Two small pipes were pushed into the compacted soil to obtain specimens for determination of the density and unconfined compression strength of the compacted clay. Shear parameters were determined for the clay and sand at their model placement densities using the direct shear test (**Table 1**).

The dry sand was sprayed from constant height of 500 mm through a funnel into the lower tank to obtain homogeneous loose material. Small tins were placed in the tank during the pouring process for computation of the density of sand. The minimum and maximum density values for the sand are reported in **Table 1**. The relative density of the produced sand was 14%. The lower tank was filled with loose sand to a level slightly above the top of the tank.

The upper tank, filled with compacted clay, was lifted and placed on the lower tank after wiping and leveling the extra sand with a leveling rod to create a perfect contact between the loose sand and the stiff clay. The two parts were fastened with bolts.

## 3.5 Test Procedure

The main objective of this investigation is to determine the bearing capacity of stiff clay overlying very loose sand for different ratios of thickness of the stiff clay over plate size (H/D ratio) and compare the bearing capacity from the experiments with those obtained from known theoretical methods. A total of six load tests were conducted; five tests on the layered soil system, i.e. stiff clay over loose sand and one test on homogeneous stiff clay. The plate sizes used for the layered soil system were 75mm, 100mm, 150mm, 200 mm and 250mm giving H/D ratios of 2, 1.5, 1.0, 0.75 and 0.6 respectively. Plate size effects on the experimental results were not expected because the stressed area at the contact of the clay with the sand is estimated, according to the 2V/IH rule, to be 400mm which is smaller than the tank diameter.

By the end of the preparation stage of the test, the steel plate was located on the stiff clay, at its center. The load cell was placed at the center of the plate and the hydraulic jack was placed on the load cell in contact with the reaction beam of the loading frame. The transducers and the load cell were connected to the data logger. It was switched on to record the displacement and load readings. The load was manually applied by the hydraulic jack at a constant settlement rate and continued to failure or until 30 mm settlement value was reached; afterwards the data logger was switched off. The test setup and procedure were verified by repeating some of the tests.

## 4. Results and Discussion

**Fig. 2** presents the pressure-settlement curves for the plates 75mm, 100mm, 150mm, 200mm and 250mmdiameters, for the cases of stiff clay overlying loose sand and that for homogeneous stiff clay. The curves show nonlinear pattern and an increase in settlement with increase in the applied load until failure was attained. The resistance to failure decreases with increasing the plate diameter.

The ultimate bearing capacity was obtained applying the tangent method and log-log method to **Fig. 2**. The ultimate bearing capacity was also computed for all cases of the model tests using equation (1), i.e. Meyerhof and Hanna (1978) method. The terms dealing with embedment depth were neglected. The soil parameters used correspond to the placement conditions during the tests, including the soil's shear parameters, density and the size of the plates. The ultimate bearing capacities obtained from the experimental test results using log-log method, tangent method and from Meyerhof and Hanna (1978) method are given in **Fig.3** for all the plate sizes.

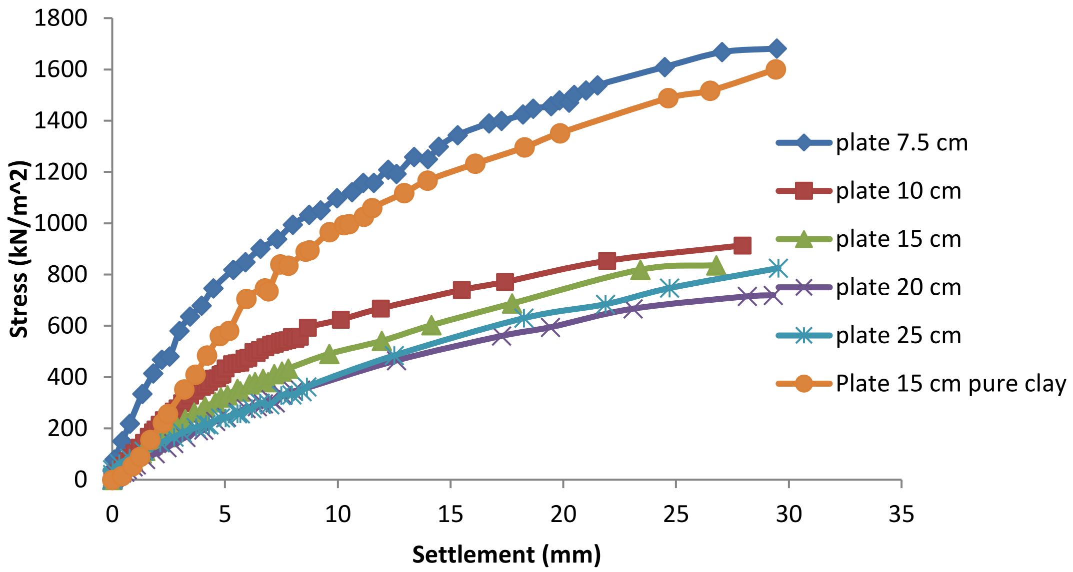


**Fig. 2: Stress versus settlement for all the tests**

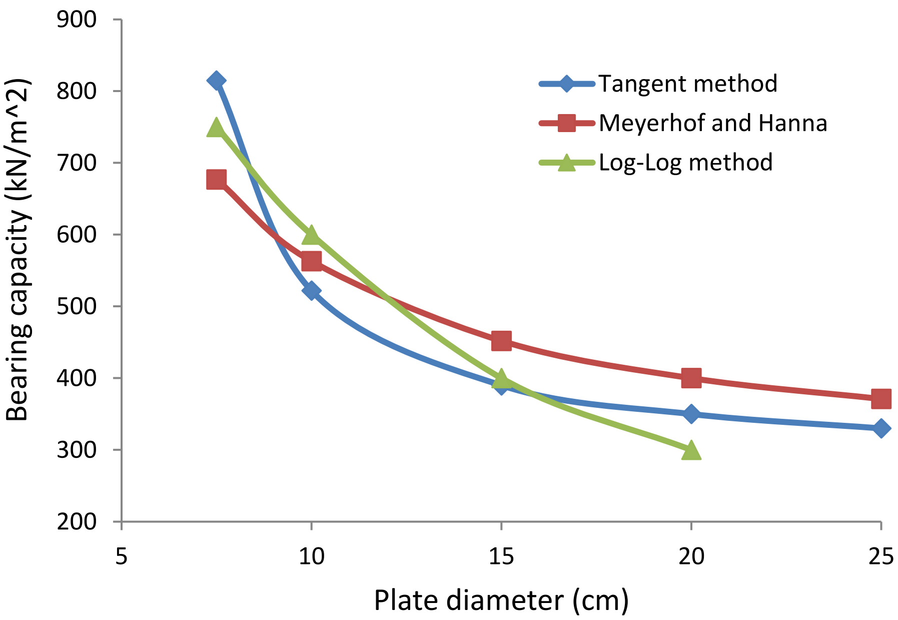


**Fig. 3: Ultimate bearing capacity ($q_u$) against plate diameter**

The ultimate bearing capacity decreased with increasing plate diameter. The tangent method gave results which are slightly lower than Meyerhof and Hanna (1978) method except for the small plate (75mm). The ultimate capacity from the log-log method deviated from the experimental results. In general, the ultimate bearing capacity increases with the increase of H/D (**Fig. 4**) for the experimental tests and for Meyerhof and Hanna equation.

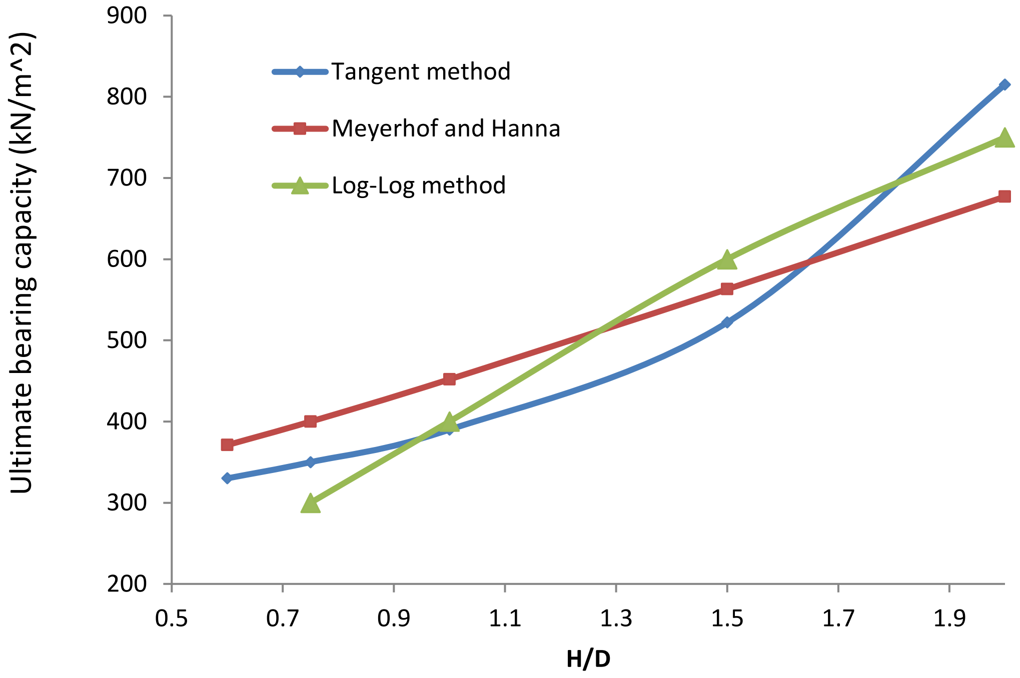


**Fig. 4: Ultimate bearing capacity against H/D ratio**

**Fig. 5** plots the load-settlement relationship for 150mm size plate when tested on homogenous and the loading test when placed on the layered soil. The bearing capacity of the homogeneous stiff clay foundation is 962 kN/$m^2$ whereas it is 390 kN/$m^2$for the case of stiff clay overlying loose sand. The loose sand caused the ultimate bearing capacity to decrease to 40% of its original value for the 150mm plate (H/D = 1.0).

The angle of friction for the stiff clay is 20$^o$ and the corresponding bearing capacity factor $N_c$ is 14.83. This $N_c$ value is applied when the stiff clay extends to great depth and the stresses do not reach the underlying loose sand. For this specific study, the loose sand will result in reduction in $N_c$ value of the upper clay. Using the general form of the ultimate bearing capacity given by Meyerhof (1963),$N_c$ was back calculated from the experimental results. The back-calculated $N_c$ values (here termed $N_C^*$) are given in **Fig. 6** for all the plate sizes. The highest $N_C^*$ value from the experimental results is 6.5 (H/D equals 2.0) and the lowest is 2.6. The loose sand caused significant reduction in $N_C^*$. The effective depth is the smallest upper layer thickness that does not allow the lower layer to affect bearing capacity; for this experimental study the effective depth is substantially greater than twice the plate diameter (>>2D).

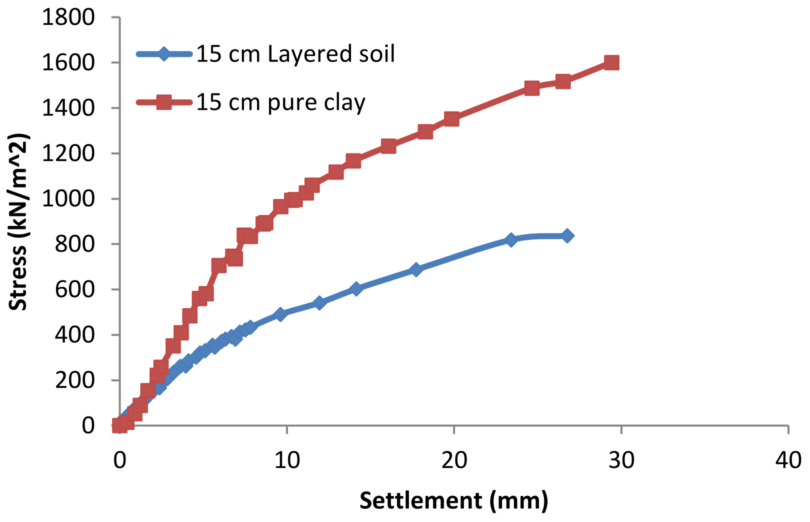


**Fig. 5: Stress settlement curves for plate size 150 mm on homogeneous stiff clay and layered soil**

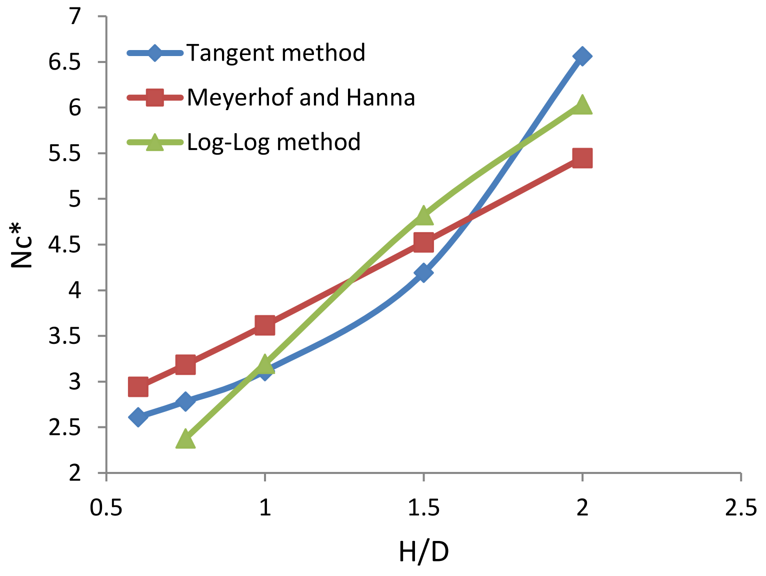


**Fig. 6: The back-calculated $N_c^*$ values for different H/D**

Meyerhof and Hanna (1978) theoretical method for the determination of bearing capacity of strong soil overlying weak soil gave good results when compared to the bearing capacity obtained from the experiments, using the tangent method. The capacities from the log-log method do not properly match with Meyerhof and Hanna. However, the ultimate capacities using Meyerhof and Hanna are up to 15% higher than those from the experiments when H/D is less than or equal to 1.5.

## 5. Conclusions

The bearing capacity of circular footings placed on stiff clay overlying very loose sand was investigated using experimental model tests for different ratios of stiff clay layer thickness (H) to footing diameter (D). The tests were performed in a steel tank divided into two parts, an upper part (150 mm high) and a lower part (600 mm high). The footings were represented by circular steel plates with diameters 75mm, 100mm, 150mm, 200mm and 250mm. The clay was compacted on a steel plate to the required density in the upper part of the tank whereas the sand was poured into the lower tank from constant height to produce loose state. The two parts were fastened together. The load was manually applied by a hydraulic jack against a reaction frame at constant strain. The loads and settlements were recorded by data logger. The soil parameters needed for bearing capacity calculations were measured in the laboratory. The ultimate bearing capacity was obtained from the test data using the Tangent and Log-Log methods. Meyerhof and Hanna (1978) theoretical equation for the case of a footing on strong soil overlying weak soil was used to compute the bearing capacity.

- The load settlement curves showed non-linear relationship between stress and settlement. The settlement increased with applied load until failure took place.
- The ultimate bearing capacity decreased with increasing plate diameter. The tangent method gave results which are slightly lower than those computed by Meyerhof and Hanna method except for the smaller plate size (H/D equals 2).
- The bearing capacity of the foundation on homogeneous stiff clay foundation is more than twice that for stiff clay overlying very loose

sand when H/D equals 1.0. This indicates significant reduction in bearing capacity of the latter caused by the very loose sand.

- The bearing capacity factor $N_C$ was back-calculated for the cases of stiff clay over loose sand to get $N_C^*$. The largest value of $N_C^*$ is 6.5 (H/D = 2.0) and the smallest value is 2.6 using the tangent method results. This indicates significant effect of the very loose sand on the bearing capacity factor Nc.
- The effective depth which is the smallest upper layer thickness that does not allow the lower layer to affect bearing capacity is much more than twice the plate diameter (>>2D)

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