

Bearing Capacity of Strip Footings Resting on Granular Soil Overlying Soft Clay

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Abstract In the present research, an analytical method is applied to determine the bearing capacity of strip footing on two layers of soil. Bearing capacity is calculated according to soil resistance beneath the foundation and a virtual retaining wall method. To determine the bearing capacity of the footing in the said method, the active and passive forces on the retaining wall are considered equal along the edges. The active and passive forces of each of the two soil layers are found, and the results are applied to calculate the footing bearing capacity. Among the many advantages of this method are the possibility to determine depth of the rupture surface beneath the footing, and the ability to study the effects of the soil's second layer on the footing bearing capacity. This study also examines the effects of soil improvement beneath the footing, as well as the depth and width of the compacted area on bearing capacity. A thorough analysis is conducted on soil layer thickness, soil cohesion and friction angle, footing depth and width, the width of the compacted soil beneath the footing, and the depth of underground water. A MATLAB program was used for calculation and deduction. In order to study the effects of various parameters on two layers of soil, results were compared with the bearing capacity of the footing on one soil layer in various situations. The bearing capacity of the footing was then compared with previous experimental methods, and the results obtained were reliable.

Keywords Two layers of soil · Soil improvement · Foundation width · Soil thickness

1 Introduction

When a structure is constructed, the soil underlying the footing is usually compacted and due to the limited compacted area, two layers of soil are made, whereby the upper layer turns tough and compact, and the lower layer weakens. In such conditions, the type of load tolerated by a certain footing and the parameters affecting bearing capacity of the footing are important factors to consider. Despite the variety of analytical methods to determine the bearing capacity of the footing on multi-layered soils, the assumptions made did not take into consideration the various parameters affecting bearing capacity of the footing, and their accuracy was not confirmed by a comparison with other experimental methods. The simple analytical method presented in this research, on the other hand, is accurate as it provides a comparison of various experimental methods that analyze different parameters affecting bearing capacity of the footing.

Prandtl surveyed strip footing on cohesive-frictional soil, and derived that rupture in two-layer soil occurs by punching shear [1]. Reissner presented a method that studies soil resistance against the uniform load placed on it [2]. Tarzaqi, Mayerhof, Hansen, Vesik, and others also presented equations for the footing bearing capacity, whereby the second layer of a two-layer soil is lower than the footing width [3–10].

Mayerhof investigated the bearing capacity of footing on compacted sand and soft clay. Results of the experiment were in agreement with the observations, as the friction angle was mobilized and there was cohesion on the rupture

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surface [11]. Cerato et al. as well as Dewaiker et al. studied the footing on a multi-layer soil model within micro-scales. They concluded that the bearing capacity of footing from experimental methods is larger than analytical methods [12, 13]. Bearing capacity of the footing on soft clay practically increases as a compacted sand layer is applied beneath the footing. Kenny et al. presented an accurate method to analyze the bearing capacity in such circumstances, and compared the results with their developed experimental models in merely sand, merely clay, and sand on clay [14]. The methods to calculate the bearing capacity of footing for multi-layer soils range from obtaining an average of resistive parameters by limiting the equilibrium to limiting the analysis [15]. Similarly, Mayerhof and Hanna presented experimental methods to study the bearing capacity of footing on multi-layer soil [16]. Burd and Frydman studied complicated models of multi-layer soil by applying the limited elements model [17]. Analytical and experimental findings revealed that the thickness effect of upper soil beneath the footing on bearing capacity of the footing depends on the following parameters: shear resistance, proportion of layers in bearing capacity, footing shape and depth, and slope of the applied load. Cassidy et al. proved that punching shear is caused by sand over clay [18]. Sharma and Madhav studied the bearing capacity of footing on compacted soil located on soft clay [19]. The compacted layer imposes uniform stress onto the soft soil with a larger width. Loading on clay is decreased linearly as distance from the footing is increased. Mayerhof and Hanna tested and presented the results of footings that were placed over compacted soil posited on soft clay [20]. In their study on the final bearing capacity of footing on the sand over clay layer, Win and Oda [21] concluded that plastic flow occurs laterally, in the direction of the clay layer, and consequently the load on the upper layer decreases the bearing capacity of the footing. Abdolhazo et al. calculated the bearing capacity of footing placed on a weaker clay layer with compacted sand [22]. They assumed the punching rupture occurs in the sand layer, and the Prandtl rupture occurs in the clay layer, which is a function of soil features, footing widths, and upper soil thicknesses. Murat et al. indicated that the model scale had no significant effect on the bearing capacity of circular footing on natural clay improved by compacted granular layers [23]. Hafez studied the bearing capacity of circular footings on the soil improved with compacted soil [24]. Ornek et al. presented an experimental model to determine the bearing capacity of footing on granular soil overlying soft clay [25]. Lee et al. determined the bearing capacity of the footing on sand over clay through centrifuge tests and the finite element method [26]. In the findings by Bowels, the effect of soil thickness beneath the footing was calculated

using the equation $H = \frac{B}{2} \tan\left(45 + \frac{\phi}{2}\right)$ where B is footing width and ϕ is soil friction angle. The effective thickness is as $2B$ [27].

Despite the many studies conducted on the reaction of footings on two soil layers, continued study on the occurred rupture in the two layers and the effects of the second layer are crucial. As previously mentioned, a simple analytical method is required to study the effects of various parameters on the bearing capacity of the footing over multi-layered soils. The present research introduces an analytical approach to find the bearing capacity of strip footing over two layers of soil. The bearing capacity can be calculated by soil stability beneath the footing and the virtual retaining wall method, wherein the active and passive forces of each soil layer are calculated, and their resultant is applied. Among its other advantages, this method can locate the rupture surface depth of the soil beneath the footing, study the effect of the soil's second layer on bearing capacity of the footing, and further analyze the effects soil improvement beneath the footing and along the width and depth of the compacted area have on the bearing capacity. The parameters under analysis in this project include soil layer thickness, soil cohesion and friction angle, footing width and depth, width of the compacted soil beneath footing, and the depth of underground water. In order to study the effects of various parameters on two-layered soils, results of this research were compared with the bearing capacity of footing on one soil layer under various conditions. Finally, the bearing capacity of the footing from the present method is compared with previous experimental methods.

2 Research Method

An analytical virtual retaining wall method, assumed along the footing edge is used to find the bearing capacity of strip footings on improved soft clay by one layer of compacted soil beneath the footing. The imposed load from the structure and the soil beneath the footing imposes an active force on the wall, while the peripheral soil resists the movement and imposes a passive force on the virtual wall. The bearing capacity of the footing is found by making the active and passive forces on the wall equal. The active and passive forces of each layer are found in two layers of soil, and the bearing capacity of the footing in the two layers is found by an equal resultant. This method has many advantages, as it can determine the depth of the rupture surface and analyze the effects of the soil's second layer in various situations. Initially, the depth of the rupture surface was found to be equal to the height of the virtual wall. The

angles η_{ae1} , η_{ae2} are made by the active surface of each layer with a horizon, and are found in each layer concerning the friction angle of that layer. As shown in Fig. 1, the angles η_{ae1} , η_{ae2} are found through the Coulomb equation. The angles η_{pe1} , η_{pe2} , on the other hand, are made by the passive surface of each layer with a horizon, and they depend on the friction angle of two soil layers. According to the available trigonometrical equations, the height of the virtual retaining wall in the second layer is found through the following equation:

$$H_2 = \left(B - \frac{H_1}{\tan \eta_{ae1}} \right) \tan \eta_{ae2} \tag{1}$$

where B is the foundation width, H_1 is the thickness of first soil layer, H_2 is the thickness of virtual wall in the second soil layer.

Equation (1) indicates that the height of the virtual retaining wall in the second layer depends on several factors, namely the footing width, the thickness of the first soil layer, and the friction angle of the first and second soil layers. Therefore, when H_2 is positive, the rupture surface enters the second layer. When it is negative, the second soil layer has no effect on bearing capacity of the footing (Fig. 2), rather bearing capacity of the footing is found only with one soil layer. The bearing capacity of the footing equation can be obtained when H_2 is positive and both soil layers affect the bearing capacity. Since the width of the compacted layer beneath the footing affects the bearing capacity, the latter is found according to the width of the compacted layer (B_s), which is larger than and equal to the footing width. Equation (2) shows that the bearing capacity of the footing can also be determined when the width of the compacted soil in dry soil is larger than the footing width, and the active force on the virtual retaining wall is the resultant of active forces in two soil layers. Since soil in the passive area

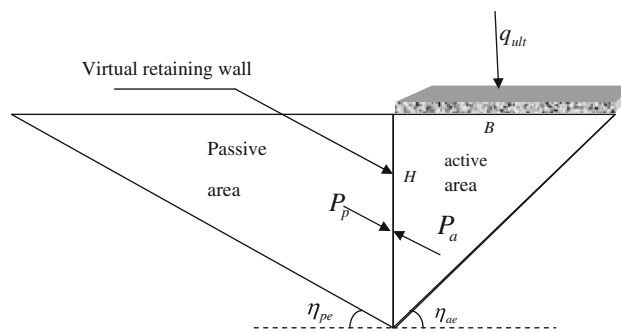


Fig. 2 Rupture surface in soil beneath foundation when virtual retaining wall is only in first layer

refers to both compacted soil and clay, the passive force on the virtual retaining wall is found by determining the soil weight in the passive area and by using the sinus rule in the triangle of the forces imposed on the passive surface, as per Eq. (3) (Fig. 3).

$$P_a = q_u k_{a1} H_1 \cos \delta_1 + q_u k_{a2} H_2 \cos \delta_2 + \frac{1}{2} k_{a1} \gamma_1 H_1^2 \cos \delta_1 + \frac{1}{2} k_{a2} \gamma_2 H_2^2 \cos \delta_2 + \gamma_1 H_1 K_{a2} H_2 \cos \delta_2 + c_1 k_{ac1} H_1 \cos \delta_1 + c_2 k_{ac2} H_2 \cos \delta_2 \tag{2}$$

$$P_p = \frac{\sin(\eta_{peave} + \phi_{ave})}{\sin(90 + \delta_{ave} + \eta_{peave} + \phi_{ave})} \left(\gamma_2 H_2 \frac{H_2}{2 \tan \eta_{pe2}} + \frac{B_s - B}{2} \gamma_1 H_1 \left(\frac{H_1}{\tan \eta_{pe1}} - B_s - B \frac{H_1 + H_2}{\tan \eta_{pe2}} \right) + \frac{1}{2} \gamma_2 H_1 \right) \tag{3}$$

Finally, the bearing capacity of the footing q_u is found by equalizing active and passive forces as follows:

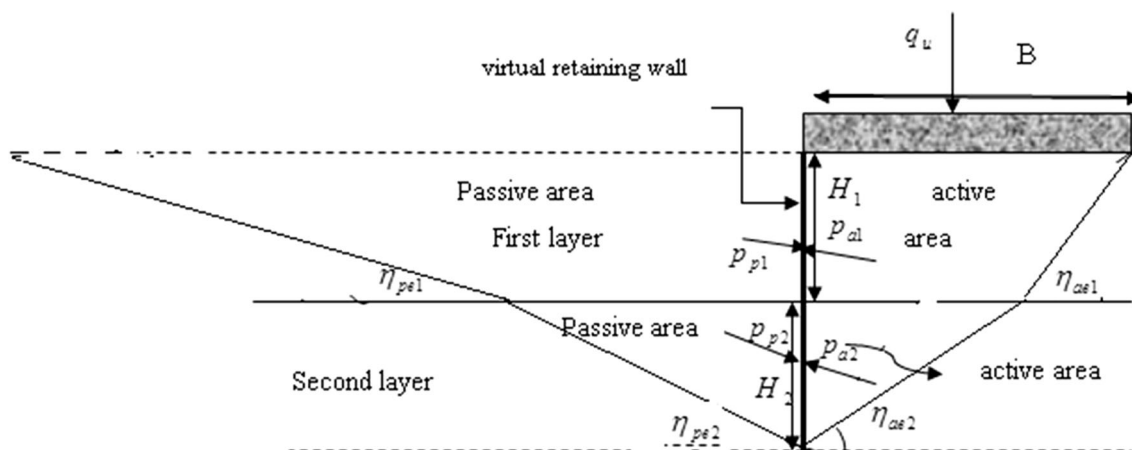
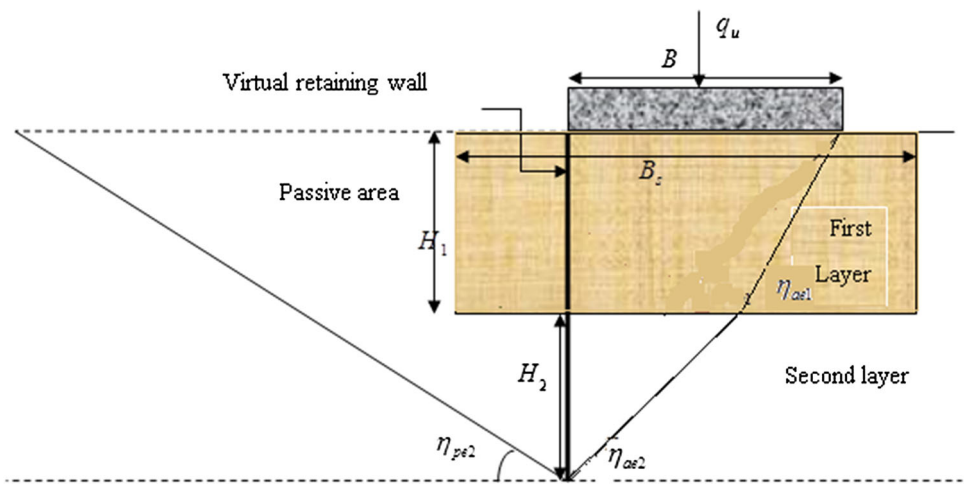


Fig. 1 Rupture surface in two soil layers with virtual retaining wall method

Fig. 3 Rupture surface in soil beneath the foundation improved with compacted soil ($B_s > B$)



$$q_u = \frac{1}{k_{a1}H_1 \cos \delta_1 + k_{a2}H_2 \delta_2} \left(P_p + \frac{1}{2}k_{p2}\gamma_2H_2^2 \cos \delta_2 + k_{p1}\gamma_2DH_1 \cos \delta_1 + k_{p2}\gamma_1DH_2 \cos \delta_2 + k_{p2}\gamma H_1H_2 \cos \delta_2 - \frac{1}{2}k_{a1}\gamma_1H_1^2 \cos \delta_1 - \frac{1}{2}k_{a2}\gamma_2H_2^2 \cos \delta_2 - k_{a2}\gamma_1H_1H_2 \cos \delta_2 + c_1k_{pc1}H_1 \cos \delta_1 + c_2k_{pc2}H_2 \cos \delta_2 + c_1k_{ac1}H_1 \cos \delta_1 + c_2k_{ac2}H_2 \cos \delta_2 \right) \quad (4)$$

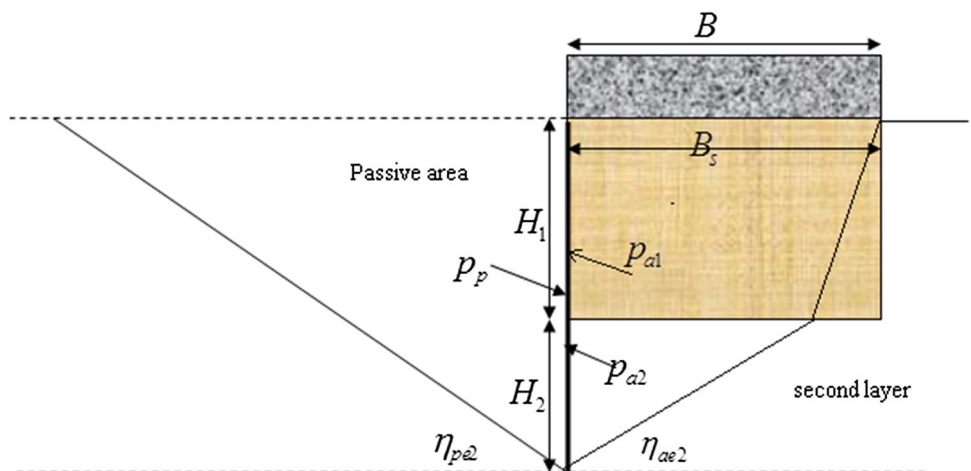
where in Eqs. (2), (3) and (4), H_1, H_2 are the height of virtual wall in two soil layers (Fig. 3), $k_{a1}, k_{a2}, k_{ac1}, k_{ac2}$ are the active coefficients of two soil layers, $k_{p1}, k_{p2}, k_{pc1}, k_{pc2}$ are passive coefficients of two soil layers, $\gamma_1, \gamma_2, c_1, c_2, \delta_1, \delta_2$ are specific gravity, cohesion and friction angle between soil and virtual wall in two soil layers, B is the foundation width, B_s is the width of compacted soil, $\eta_{peave}, \phi_{ave}, \delta_{ave}$: average of passive surface angles, friction angle and friction angles between soil and wall in two soil layers.

According to Eq. (4), the effect of the width of compacted layer in passive area is seen in P_p . To obtain P_p , the sinus rule should be used to find the soil weight in the passive area, and multiply: $\frac{\sin(\eta_{peave} + \phi_{ave})}{\sin(90 + \delta_{ave} + \eta_{peave} + \phi_{ave})}$.

The passive layer width, when larger than the footing width, indicates the existence of two types of soil in the passive area. The average of friction angles and the passive surface angles were applied in the P_p equation, and the effects of increasing the compacted layer width in P_p , as well as, the bearing capacity of the footing q_u are quite clear.

The bearing capacity of the footing is then found where the compacted layer width is equal to the footing width (Fig. 4). Here, clay exists in the soil passive area, and the two available layers in the active area are the compacted layer with H_1 thickness and the clay layer with H_2 thickness. As a result, the active force on the virtual retaining wall is the resultant of active forces in two soil layers, and the passive force on the wall comes from clay. In this

Fig. 4 Rupture surface in soil beneath the foundation ($B = B_s$)



condition, the footing bearing capacity is determined as follows:

$$\begin{aligned}
 q_u = & \frac{1}{k_{a1}H_1 \cos \delta_1 + k_{a2}H_2 \cos \delta_2} \left(\frac{1}{2} k_{p2}\gamma_2(H_1 + H_2)^2 \cos \delta_2 \right. \\
 & + k_{p2}\gamma_2 D(H_1 + H_2) \cos \delta_2 - \frac{1}{2} k_{a1}\gamma_1 H_1^2 \cos \delta_1 \\
 & - \frac{1}{2} k_{a2}\gamma_2 H_2^2 \cos \delta_2 - k_{a2}\gamma_1 H_1 H_2 \cos \delta_2 \\
 & + c_2 k_{pc2}(H_1 + H_2) \cos \delta_2 + c_1 k_{ac1} H_1 \cos \delta_1 \\
 & \left. + c_2 k_{ac2} H_2 \cos \delta_2 \right). \tag{5}
 \end{aligned}$$

The active and passive forces occur in the two soil layers beneath the footing (Fig. 1), and the bearing capacity of the footing is found by making the two forces equal:

$$\begin{aligned}
 q_u = & \frac{1}{k_{a1}H_1 \cos \delta_1 + k_{a2}H_2 \cos \delta_2} \left(\frac{1}{2} k_{p1}\gamma_1 H_1^2 \cos \delta_1 \right. \\
 & + \frac{1}{2} k_{p2}\gamma_2 H_2^2 \cos \delta_2 + k_{p1}\gamma_2 D H_1 \cos \delta_1 \\
 & + k_{p2}\gamma_1 D H_2 \cos \delta_2 + k_{p2}\gamma_1 H_1 H_2 \cos \delta_2 \\
 & - \frac{1}{2} k_{a1}\gamma_1 H_1^2 \cos \delta_1 - \frac{1}{2} k_{a2}\gamma_2 H_2^2 \cos \delta_2 \\
 & - k_{a2}\gamma_1 H_1 H_2 \cos \delta_2 + c_1 k_{pc1} H_1 \cos \delta_1 \\
 & \left. + c_2 k_{pc2} H_2 \cos \delta_2 + c_1 k_{ac1} H_1 \cos \delta_1 + c_2 k_{ac2} H_2 \cos \delta_2 \right) \tag{6}
 \end{aligned}$$

Equations (4), (5), and (6) are related to the conditions where the soil beneath footing is dry and when the level of underground water is associated with virtual retaining wall method in respect of active and passive surfaces, the effect of underground water on soil density is indicated in the

three mentioned equations. Underground water location affects not only the soil density, but also the bearing capacity of the footing. As shown in Fig. 5, the active and passive forces on the virtual retaining wall vary according to the existence of underground water in the first or second layer. MATLAB is used to identify the effects of various parameters (including footing width and depth, first layer thickness and width, first and second layer cohesion and friction angle, and the underground water depth) on the bearing capacity of footing and the obtained equations from the virtual retaining wall method. In the next section, results are shown as normalized charts. To verify the accuracy of the proposed analytical method, results of the proposed method are compared with previous experimental results conducted by other researchers.

3 Results and Discussions

Results presented here from the analytical method are shown as normalized charts. The results are compared with previously obtained results by other researchers. The effects various parameters have on the bearing capacity of the footing on two soil layers are further analyzed through normalized charts.

3.1 Comparing the Presented Analytical Method with Experimental Results

Hafez et al. [24] used an experimental method to determine the bearing capacity of footing on compacted soil over soft clay (Fig. 6). Here, the results of the Hafez et al. experimental method are compared with those of the presented analytical method [24]. In the studied model, the

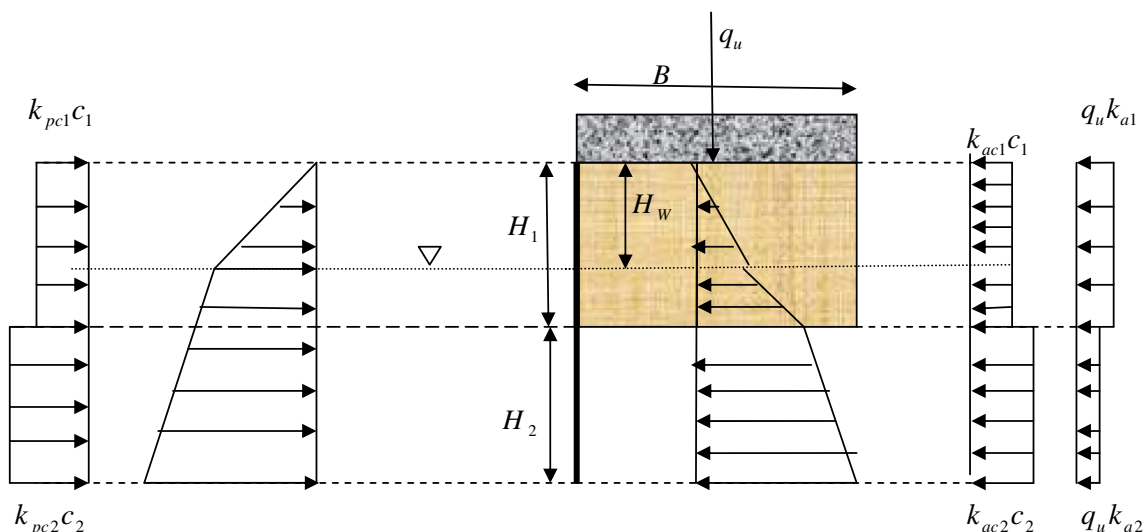


Fig. 5 Forces on virtual retaining wall in weak soil improved with compacted soil

Fig. 6 Experimental model presented by Hafez [24]

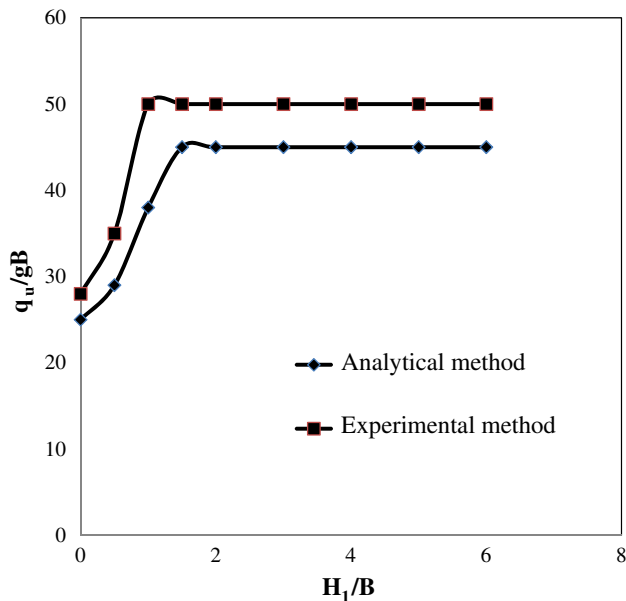
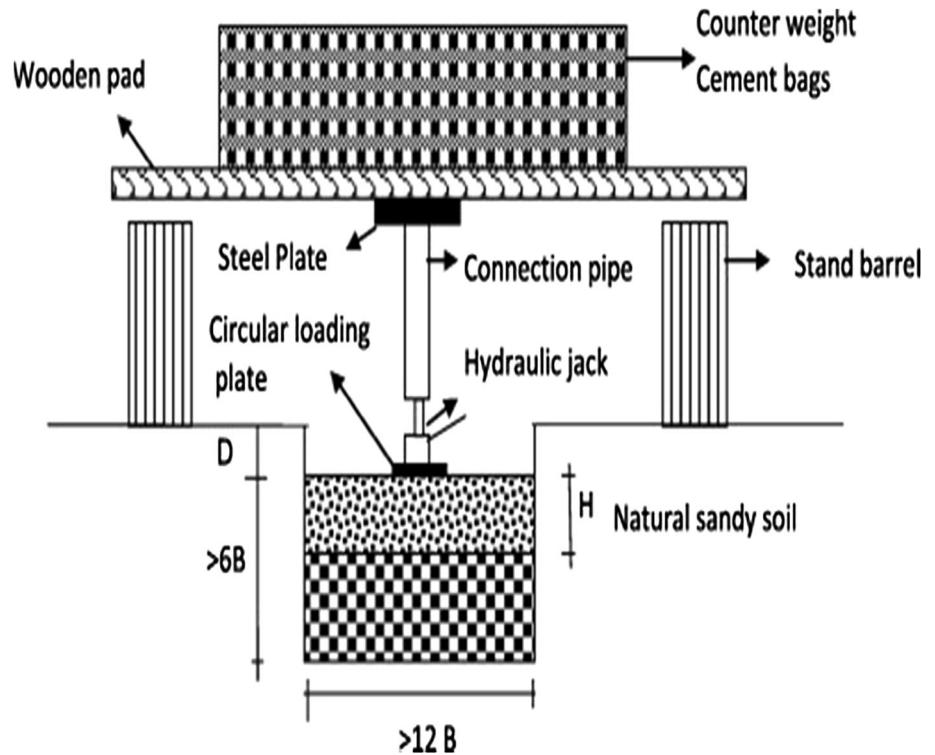


Fig. 7 Comparing effect of compacted layer thickness to footing width on footing bearing capacity with presented analytical method and experimental method presented by Hafez [24] ($D/B = 0$, $B_s/B = 1$)

compacted soil used had a 21 kPa cohesion, a 20 kN/m^3 density, a friction angle of 3° , and a footing width (B) of 0.2 m. Figure 7 illustrates the thickness of the compacted soil layer on the footing width ratio (H_1) and its effects on the bearing capacity of footing that is normalized in

proportion to the multiplied density and the normalized footing width. While the analytical method presented smaller results than the experimental method, nonetheless the difference was insignificant. It should be noted that the ratio of the footing depth (D) to the footing width was assumed zero, and the width of the compacted soil layer (B_s) was considered the same as the footing width. Figure 7 indicates that increasing the compacted soil layer up to the footing width in the experimental method will increase the bearing capacity of the footing. In addition, increasing the compacted soil thickness to more than the footing width does not create further changes in the bearing capacity of the footing.

However, by increasing layer up to 1.5 times as much as the thickness of compacted soil than the footing width in analytical method, the bearing capacity of the footing increases and the exceeding does not affect the bearing capacity of the footing. If the thickness of the compacted soil exceeds, the compacted soil layer alone is placed on the rupture surface, and the bearing capacity of the footing is found on a single soil layer. Figure 7 shows the differences of both experimental and analytical methods in terms of the compacted soil layer thickness, all from assumptions made in analytical methods, the considered scale, and the errors occurred in experimental methods. A thorough analysis on the presented analytical method proves that the thickness of compacted soil with up to 1.5 times the footing width does not affect the bearing capacity of the footing. As stated earlier, the

height of the virtual retaining wall in the second layer depends on the friction angle of the first and second layers, the footing width, and the thickness of the compacted layer. Figure 7 shows that the maximum increase of the bearing capacity of the footing exceeds the analytical method by 80 %, and the experimental method by 78 %, which shows that the two methods give similar results. In the analytical method, any increase in the thickness of the compacted layer results in a higher rupture surface angle of the active area with a horizon and a lower active force on the virtual retaining wall that increases the bearing capacity of the footing. The fact that the height of the virtual retaining wall or the effective thickness of the rupture surface depends on several factors, including the friction angle of two soil layers, the footing width, the compacted soil layer thickness, the assumptions made in the present case study, and the assumption of clay with a low friction angle in the second layer, reveals that the effective thickness from the analytical method is about 1.5 times the footing width, but varies as the resistive features of the second layer, such as the soil friction angle, change. Figure 8 compares the manner in which the ratio of the compacted soil width to the footing width increases the bearing capacity of the footing in both analytical and experimental methods. Results reveal that although the bearing capacity from the analytical method is smaller than that of the experimental method, the results are nonetheless close and acceptable. Results further showed similar changing trends in the bearing capacity of the footing, by increasing the compacted soil layer width for both methods. x in Fig. 8 represents the increase in the

compacted layer thickness from two sides of the footing. Increasing the footing width of x in the experimental model by up to two times caused a higher bearing capacity of the footing, but exceeding that amount did not have any further effects on the bearing capacity. The effective width obtained in the analytical method however, is around 1.2 times the footing width. The effective width is obtained when the clay’s friction angle in the lower soil is low. When the soil friction angle changes, so does the effective width, because the angle of active and passive rupture surfaces depends on the soil friction angle. According to the results, increasing x/B from 0 to 1.2 times the footing width in the analytical method will increase the bearing capacity of the footing by 3–4 times, which implies that the width of the compacted layer has a significant effect on the bearing capacity. Increasing the width of the compacted layer beneath the footing results in a higher passive force on the virtual retaining wall and a higher bearing capacity of the footing, where the entire width of the passive rupture surface is formed by the compacted layer. Exceeding the width of the mentioned layer does not affect the bearing capacity of the footing. In this section, the results of the presented analytical method are compared with the results presented by Orneka et al. [25] in their experimental method [25]. The effects of the varying thickness of the compacted soil on the bearing capacity of footing are compared in the two methods. Figure 9 illustrates the ratio of BCR (the bearing capacity of footing with a compacted layer) to the bearing capacity of footing without the said layer. Results of the analytical and experimental methods are close and acceptable. Figure 9 shows that by increasing the thickness of the compacted

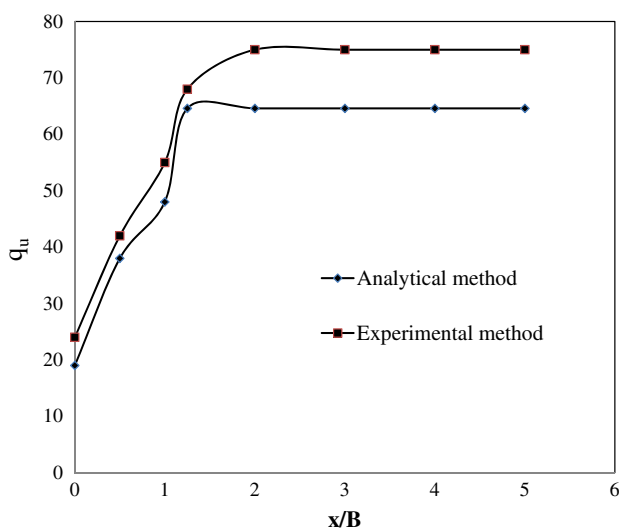


Fig. 8 Comparing effect of increasing compacted layer width to footing width on footing bearing capacity with presented analytical and experimental method [24] ($D/B = 0, H_1/B = 1$)

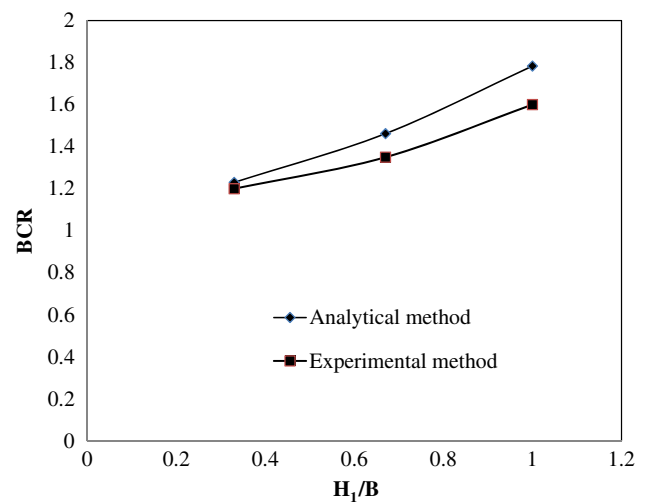


Fig. 9 Comparing effect of compacted layer thickness to footing width on footing bearing capacity normalized with footing bearing capacity without improved soil with presented analytical and experimental method [25] ($D/B = 0, B_s/B = 1$)

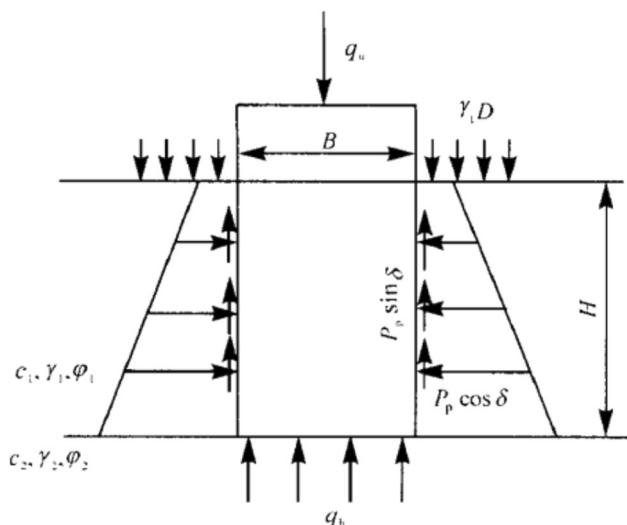


Fig. 10 Method of Meyerhof and Hanna [20]

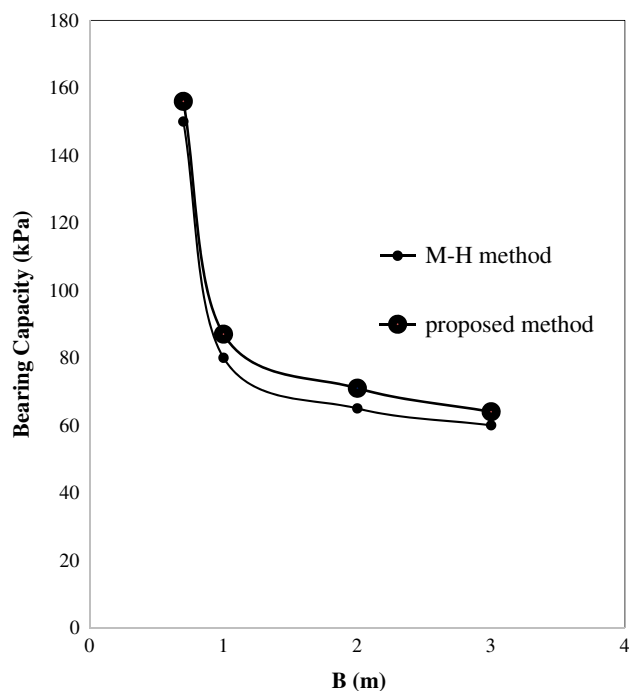


Fig. 11 Relationship between bearing capacity and foundation width (first layer: height = 0.75 m, $\phi = 19.5^\circ$, $c = 7$ kPa, $\gamma = 19$ kN/m³, second layer: $\phi = 10^\circ$, $c = 5$ kPa, $\gamma = 19$ kN/m³)

layer to reach the footing width will cause a 52 % increase in the analytical method, a 60 % in the experimental method and an 80 % increase in the presented experimental method by Hafez et al. Findings show that the results of the analytical method are closer to the experimental method results obtained by Orneka et al. Overall, the analytical method presented reliable results compared to the other methods. Increasing the thickness of the compacted layer decreases the active force on the virtual wall and the bearing capacity of the footing.

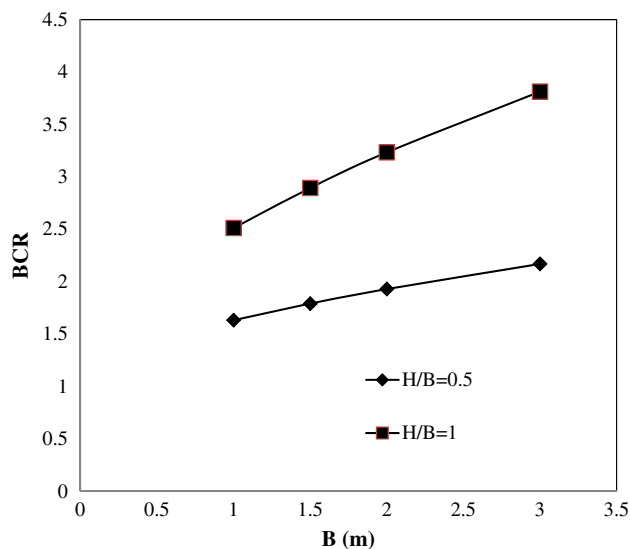


Fig. 12 Effect of footing width on increasing footing bearing capacity in various compacted layer thicknesses beneath the footing ($D/B = 0$, $B_s/B = 1$)

3.2 Comparison of the Presented Analytical Method to that of Meyerhof and Hanna

According to the Meyerhof and Hanna theory, the bearing capacity of the footing on layered soils is estimated by considering a simplified mechanism (Fig. 10), in which the underlying weak soil is assumed to be in a state of passive failure along a vertical plane [20]. In the current case study, various foundation widths of the presented analytical bearing capacity are compared with the results of Meyerhof and Hanna (Fig. 11). Results indicate good agreement, thereby proving that the proposed analytical method is not only reliable, but is also more capable than the Meyerhof and Hanna method. Our proposed method can determine the effect of the compacted soil width on the footing bearing capacity.

3.3 Parametric Studies

The proposed analytical method is used in this section to further analyze the effects of the footing width and depth, the thickness of the compacted layer, the depth of underground water, and the ratio of shearing resistance of the soil to the bearing capacity of the footing. Calculation is done in MATLAB, and the results are shown as normalized charts.

3.3.1 Effect of Foundation Width

The manner in which the bearing capacity of the footing affects the footing width is further analyzed in this section. The compacted soil beneath the footing lacks

cohesion and has a friction angle of 45° and a 20 kN/m^3 density. The clay beneath the footing has 10 kPa cohesion, 5° friction angle, and 19 kN/m^3 density. As shown in Fig. 12, increasing the footing width results in higher BCR (i.e. the ratio of the bearing capacity of the footing with compacted layer to the bearing capacity of the footing without the said layer). According to Fig. 12, where $H_1/B = 0.5$, BCR is increased by 30 %, as the footing width is changed from 1 to 3 meters. While, where $H_1/B = 1$, BCR increases by 50 %, and the effect of the compacted layer thickness become obvious. An increase in the footing width causes an increase in the virtual retaining wall and a deeper rupture surface as well. While, increasing passive force on the virtual retaining wall increases the bearing capacity, increasing thickness of the compacted layer reduces active force on the virtual retaining wall and is more effective in changing the bearing capacity.

3.3.2 Effect of Foundation Depth

Increasing footing depth exerts more passive force on both the virtual retaining wall and the bearing capacity of the footing. Figure 13 compares the footing depth for two conditions, the first, where clay is improved with compacted soil, and the second, where clay is the only existing soil. Results show that the footing depth has a greater effect on increasing the bearing capacity of the footing in a single layer of clay as opposed to two layers of soil. This is mainly because in the latter condition, the vertical force from the footing width in each layer is multiplied by both the passive force of that layer and the passive force of the frictional compacted layer, and is thereby stronger than the

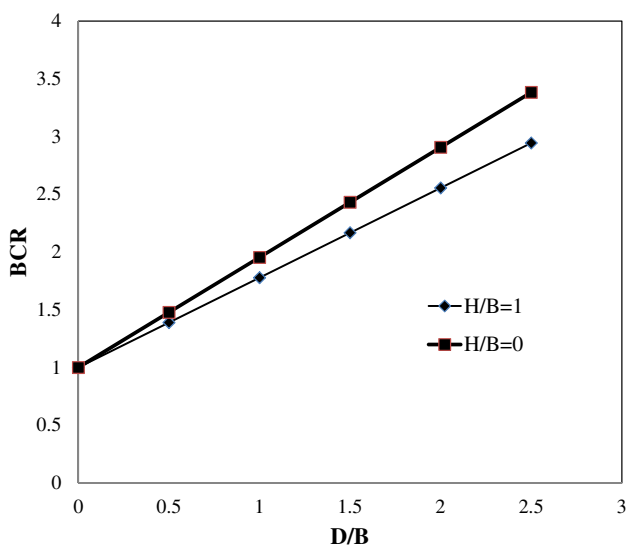


Fig. 13 Effect of footing depth on footing bearing capacity in various compacted layer thicknesses ($B_s/B = 1$)

passive force of clay. As the passive force in a single layer of soil is 1, footing depth of a single soil layer is more effective on the bearing capacity of the footing than a two-layer soil. The difference between having a one-soil layer or two soil layers on the bearing capacity becomes larger as the footing depth is increased. For example, increasing footing depth by up to 1.5 times the footing width increases the BCR of one clay layer by 30 % higher than the compacted soil clay layer. While, increasing the same by up to 2.5 times causes a 48 % growth.

3.3.3 Effect of Underground Water

If underground water is placed within the created rupture surface beneath the footing, the bearing capacity of the footing changes per the depth of underground water depth. As shown in Fig. 5, the underground water affects the stress triangle from soil weight and changes the stress slope on a virtual retaining wall, even with the underground water and soil layer change. Figure 14 shows that increasing the water depth (H_w) by 1.5 times the footing width, increases the bearing capacity of the footing; any amount exceeding this depth does not affect the bearing capacity of the footing because the underground water goes beyond the rupture surface. Figure 14 also shows that the ratio of BCR in the bearing capacity of the footing in underground water is equal to the bearing capacity of the footing without it. According to the results, the presence of underground water on the ground decreases the bearing capacity of footing by roughly 40 % compared to conditions without underground water. In addition, where $H_w/B = 1$, the bearing capacity of footing decreases by 20 % compared to conditions without underground water.

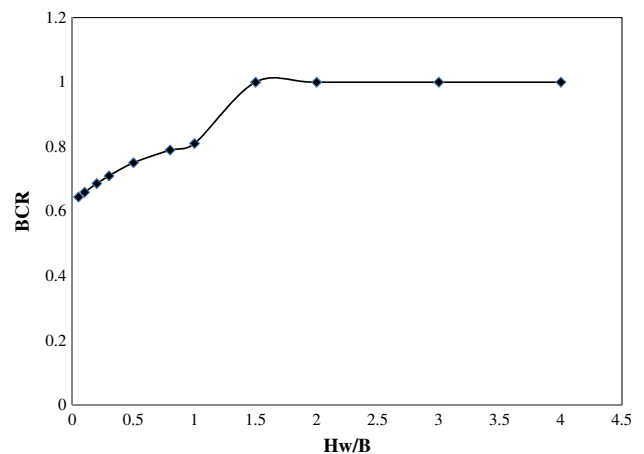


Fig. 14 Effect of underground water level on footing bearing capacity in two soil layers condition ($H/B = 1$, $B_s/B = 1$, $D/B = 0$)

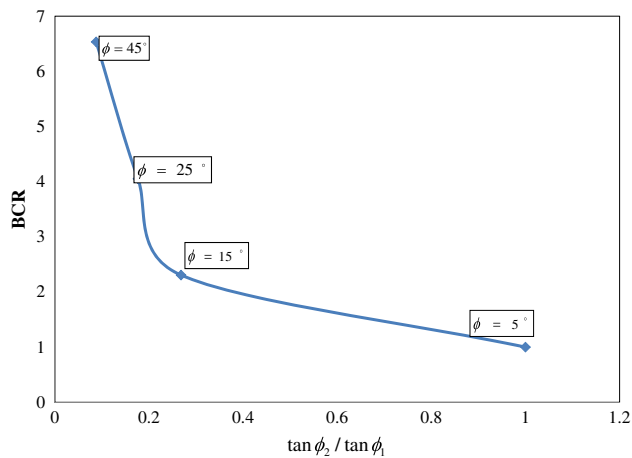


Fig. 15 Effect of friction angle of second soil layer to first soil layer on footing bearing capacity ($H/B = 1$, $B_s/B = 1$, $D/B = 0$)

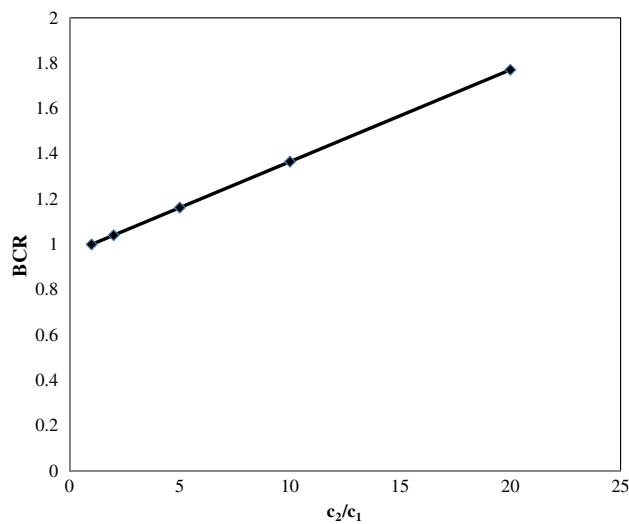


Fig. 16 Effect of cohesion of second layer to first layer on footing bearing capacity in two soil layers condition ($H/B = 1$, $B_s/B = 1$, $D/B = 0$)

3.3.4 Ratio of Shear Resistance in Two Soil Layers

Figure 15 shows the bearing capacity of the footing in a soil layer with a normalized friction angle of 5° , along with the bearing capacity of the footing in various friction angles of the compacted layer. It is also assumed that the two soil layers have similar cohesion. Clearly, the friction angle of the compacted layer affects the bearing capacity of the footing significantly. Where the friction angle of the compacted layer is 45° , the bearing capacity of the footing increases by 6.5 times as much. In fact, the more the friction angle of the compacted layer, the more the growing slope of the bearing capacity of the footing becomes. As previously mentioned, any change in friction angle decreases the height of the virtual retaining wall and the

rupture angle of active and passive areas, which evidently affect the passive and active force on both the virtual retaining wall and the bearing capacity of the footing. Figure 16 illustrates the cohesion ratio of the second soil layer to the first layer to the normalized bearing capacity, all with equal friction angles. According to the results, when the ratio of the second layer of the cohesive soil to the first layer equals 20, the bearing capacity of the footing increases by 80 %, as compared to the presence of the first layer alone. In addition, the effect that the friction angle of a two-layered soil has on increasing the bearing capacity of the footing is more than the ratio of two cohesive layers, because the friction angle affects not only the depth of the rupture surface, but also the angle of passive and active rupture surfaces. The cohesive effect on the bearing capacity of the footing is shown as active and passive stresses $k_{pc}c$, $k_{ac}c$ on the virtual retaining wall. As changes in cohesion can cause changes in k_{pc} , k_{ac} factors, the effect of friction angle on the bearing capacity of the footing is more than that of cohesion.

4 Conclusions

In the present research, the bearing capacity of the footing on improved clay with compacted soil is found by our analytical method, which is defined according to the virtual retaining wall. This wall is assumed to have equal active and resistive forces on the footing edge, where the bearing capacity of the footing is found. The presence of two soil layers to find the bearing capacity of the footing requires equal active and resistive forces on the wall. Results of our analytical method were compared with experimental and analytical methods applied by other researchers. Results of the comparison validated our analytical method. A thorough analysis on the effects of various parameters on the bearing capacity of the footing over improved clay with compacted soil led to the following conclusions:

The effective thickness of the compacted layer is about 1.5 times as much as the footing width; increasing thickness of the compacted layer increases the bearing capacity of the footing by 80 %.

The effective compacting width to the footing edge is about 1.2 times the footing width in the proposed analytical method.

An increase in the footing width from 1 to 3 m, where the ratio of the compacted layer thickness to the footing width is 1, increases bearing capacity of the footing by 50 %. Results also indicated that by increasing the thickness of the compacted layer, the footing width on bearing capacity of the footing would increase as well.

The increase of the footing depth increased both the passive force on the virtual retaining wall and the bearing

capacity. In addition, increasing the thickness of the compacted layer reduces the depth of the bearing capacity.

Underground water will affect the bearing capacity of the footing by up to 1.5 times the footing width, and anything exceeding that amount will not affect the bearing capacity of the footing. Where the ratio of the water depth to the footing width is 1, the bearing capacity of the footing decreases by about 20 %, as compared to conditions without underground water.

The results showed that the soil friction angle affects not only the rupture surface, but also both active and passive rupture surfaces. Cohesion, on the other hand, does not affect the rupture surface. In conclusion, the effect of the friction angle on the bearing capacity of the footing is more than the cohesion of two soil layers.

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