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ANALYTICAL PREDICTION OF CAPACITY VARIATION FOR ISOLATED FOOTINGS CONSIDERING ADJACENT FOUNDATIONS

Md. Montaseer Meraz*[1], Md. Tanjid Mehedi[2] and Nusrat Jahan Mim[3]

[1] *Undergraduate Student, Khulna University of Engineering and Technology, Bangladesh, e-mail: merazkuet36@gmail.com*

[2] *Undergraduate Student, Khulna University of Engineering and Technology, Bangladesh, e-mail: mdtanjidmehedikuet16@gmail.com*

[3] *Undergraduate Student, Khulna University of Engineering and Technology, Bangladesh, e-mail: nusratjahankuet@gmail.com*

***Corresponding Author**

ABSTRACT

Under working load conditions, foundation settlement is a critical design consideration. Well-designed foundations cause stress-strain states in the soil that are neither linear elastic nor perfectly plastic. Often, rather than bearing capacity, settlement dictates the construction of footings on sandy soil as well as soft clay condition. Settlement forecasts are therefore vital to the development of shallow foundations. The effect of surrounding footings is often neglected while assessing the geotechnical capacity of isolated footing considering permissible settlement criteria. In this study, the impact of a variable distanced surrounding footing is assessed under soft soil conditions. A finite element analysis is performed using geotechnical finite element analysis software PLAXIS. A substantial capacity variation is observed with varying numbers of footings and distances. Thus the consideration of this capacity variation can predict more safer design.

Keywords: *Settlement, Bearing capacity, Soft soil, finite element analysis, PLAXIS*

1. INTRODUCTION

Bearing capacity and settlement characteristics of soils are major considerations among geotechnical engineers since they have a considerable impact upon the foundation system. The mechanical features of the soil i.e., shear strength, unit weight as well as the physical characteristics of foundation i.e., shape, size, depth mainly influence the behaviour of foundations on both horizontal and sloped surface (Acharyya & Dey, 2017). The distribution of soil pressure beneath a footing is determined by the soil types, foundation depth, the rigidity of the footing and soil (Chavarrıa, Rojas, & Elizondo, 2017). It is customary in designing to consider that soil pressures are uniformly distributed. But when a rigid footing is pressured and stands upon sandy soil, the sand along the footing's edges keeps shifting laterally which causes reduction in soil pressure along the borders of the footing, but the soil distant from the footing's borders is comparatively contained. When the footing is placed upon the clay, the soil beneath it deflects in a bowl-shaped depression, reducing pressure underneath the footing's centre (Chavarrıa et al., 2017).

The recent surge of industrialization in the Khulna regions of Bangladesh has led to a plethora of residential and commercial constructions. The foundations of such structures are often shallow. Differential settlements of shallow foundation are common, leading to the load distribution from the strongly loaded inner column to the lightly loaded outer columns (Roy & Engineering, 2001). This differential settlement is inevitable although the structure is supported by a uniform soil medium due to uneven stresses on the supporting soil. The influence of differential settlement of footings is overlooked in the usual structural analysis approach used for most construction designs. This could result in underestimating of force amounts in some components, which could lead to dangerous design and disaster. A numerical modeling is required to determine the realistic capacity variation for isolated footings in advance.

Numerous researchers have recently attempted to assess the bearing capacity of various types of footings with different circumstances, aspect ratios, or embedment depths. The theoretical ultimate bearing capacity of two interfering strip footings lying on soils was investigated (Das, Larbi-Cherif, & foundations, 1983; Kumar, Bhoi, & engineering, 2008; Kumar & Ghosh, 2007; Kumar, Kouzer, & geomechanics, 2008; Saran & Agarwal, 1974; Stuart, 1962; West & Stuart, 1965) and revealed that the failure zones beneath the footings influence one another when two strip footings are contacted closely enough, resulting in a considerable increase in ultimate bearing capacity. According to the investigations (Ghosh & Kumar, 2009; Lavasan, Ghazavi, & Foundations, 2012; Lotfizadeh & Kamalian, 2016; Naderi, Hataf, & Geomembranes, 2014; Srinivasan, Ghosh, & Geoengineering, 2013) done for evaluating the effect of distance on capacity with equivalent loads, two closely spaced footings have a higher ultimate carrying capacity than a single isolated footing. The efficiency factors decline as the distance between the footings expands (Ghosh & Kumar, 2009; Lee, Eun, & geotechnics, 2009). The acquired data from those investigations revealed less efficiencies than anticipated by Stuart's theoretical study (Stuart, 1962). Because of the unpredictability of empirical formulations, various numerical analysis procedure including finite element analysis (FEA) (Gourvenec, Randolph, & Kingsnorth, 2006; Yun, Bransby, & foundations, 2007; Zhu, 2004), upper bound analysis (Yu, Huang, & Zhang, 2015; Yun et al., 2007), method of characteristics (Gholami, Hosseininia, & Engineering, 2017; Kumar & Ghosh, 2005; Tant, Craig, & Foundations, 1995) has been utilized for investigating the bearing capacity. The maximum studies were restricted in the fairly shallow embedment where D/B up to 2.5. Salgado, Lyamin, Sloan, and Yu (2004) investigated the bearing capacity factors of circular, strip and rectangular footings with varying embedment ratios and aspect ratios up to D/B = 5, whereas Edwards, Zdravkovic, and Potts (2005) examined the circular, strip footings in homogeneous clay with embedment ratios up to 4.

Till now, most experimental and theoretical studies have been intended to examine bearing capacity, but there are relatively limited literatures connected to laboratory or numerical analyses on capacity variation for isolated footings with varying distances and amounts of footings. Due to the abundance of isolated footings in Bangladesh's southwestern region, the current study intends to provide an analytical methodology for forecasting capacity variation for isolated footings when surrounding foundations are taken into account as well as new correlations are predicted that are justifed by Terzaghi and Meyerhof equation.

2. METHODOLOGY

The finite element mathematical model was created using geotechnical finite element analysis software PLAXIS 2D (Brinkgreve et al., 2016). The footing was designed as a stiff body with a mesh that was the same as the earth around it. It was possible to replicate the interaction between the footing and the nearby soil by using contact pairs. At the footing base, smooth and rough interactions were simulated to see how they would react. The contacts along the perimeter of the footing base were allowed to move. Here, "B" denotes the square footing dimension, which was determined to be 2m. As illustrated in Figure 1, Condition A is a single isolated footing, but Condition B (Figure-2) is the same isolated footing surrounded by similar-sized footings at B distance. At 1.5B distance, Condition C reflects the same central footing as Condition B (Figure-3). Finally, in Condition D, the footing is surrounded by footings of comparable size at a 2.5B distance (Figure-4). All the conditions were analzed considering 50mm settlement.

To develop the mathematical model, the simple strain Mohr-Coulomb model with 15 node elements was used; also, it was also assumed that the soil attribute had no water table influence. The investigation included well-graded sandy soils and clayey sands, as these soil types are prevalent in the surrounding region. The following table summarizes the qualities of these soils.

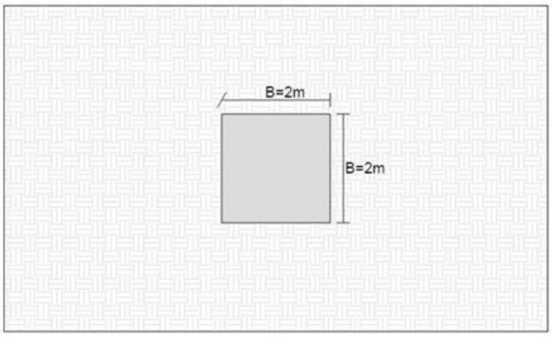

Fig-1 Condition A

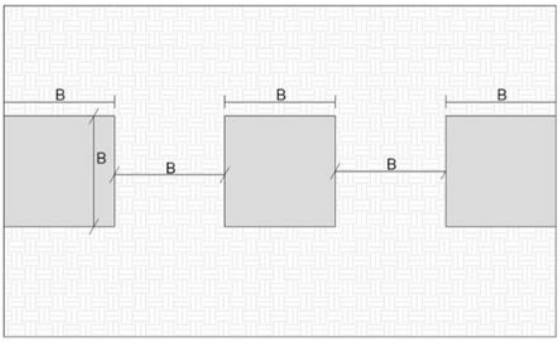

Fig-2 Condition B

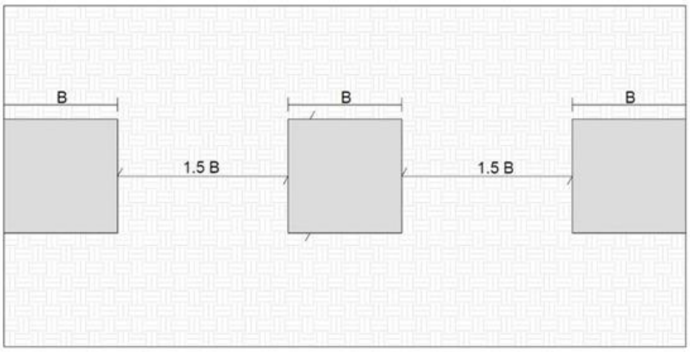

Fig-3 Condition C

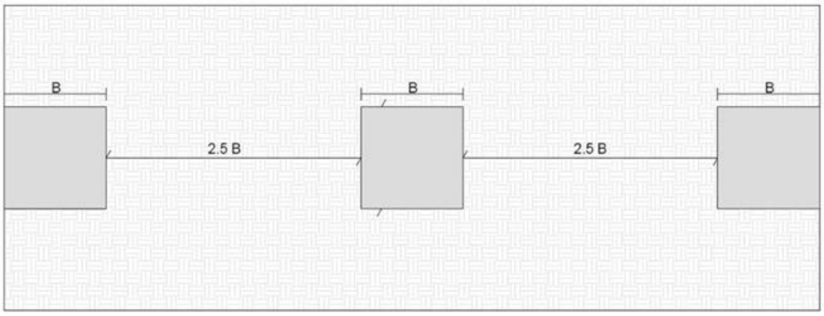

Fig-4 Condition D

Table 1: Parameters for Well Graded Sand

Parameter	**Name**	**Value**	**Unit**
Material model	*Model*	Mohr-Coulomb	-
Type of material behaviour	*Type*	Drained	-
Soil unit weight below phreatic level	γ_{unsat}	17	kN/m^3
Soil unit weight above phreatic level	γ_{sat}	20	kN/m^3
Permeability in horizontal direction	k_x	1	m/day
Permeability in vertical direction	k_y	1	m/day
Young's modulus	E_{ref}	13000	kN/m^2
Poisson's ratio	v	0.3	-
Cohesion (constant)	c_{ref}	1	kN/m^2
Friction angle	ϕ	31°	-
Dilatancy angle	ψ	0	-

Table 2: Parameters for Clayey Sands

Parameter	Symbol	Value	Unit
Material model	Model	Mohr-Coulomb	-
Type of behaviour	Type	Drained	-
Weight above phreatic level	γ_{unsat}	16	*kN/m^3*
Weight below phreatic level	γ_{sat}	18	*kN/m^3*
Permeability in horizontal direction	k_x	1	m/day
Permeability in vertical direction	k_y	1	m/day
Young's modulus	E'	5000	*kN/m^2*
Poisson's ratio	ν'	0.35	-
Cohesion	c'_{ref}	5	*kN/m^2*
Friction angle	ϕ	20	-
Dilatancy angle	ψ	0	-

3. RESULT AND DISCUSSION

3.1 Effect of the footing in sandy soil

As shown in Figure 5, Condition A has only isolated footing; as a result, the pressure bulb develops with gradual displacement, and the depth of the pressure bulb is the least of the three. Because there are several footings in Condition B and the distance between them is the shortest, the pressure bulb of those footings interacts with one another and generates the highest settlement, despite the fact that the soil profile is similar. To demonstrate the difference between Conditions A and B, the 12 mm settlement layer in Condition B is located higher elevation than the one in Condition A. The displacement layer for condition C is much higher than for conditions A and D. Because the in-between distance is just 1.5 times the length of the footing, the pressure bulb of the centre footing interacts with the other two at a higher state. Finally, in Condition D, several footings are present, but the in-between distance for the footings is 2.5 times the length of the footing. As a result, the pressure bulbs of each separate footing are hardly able to interact with one another.

The bearing force vs. displacement curve for all circumstances at sandy soil is shown in Figure 6. Under condition A, the single isolated footing can withstand 332 kN/m force, which is the maximum bearing capacity for 50 mm settlement. Condition B, on the other hand, found a nearly 9.5 percent lower bearing force than condition A when multiple footing action on sandy soil was examined with the shortest in-between distance. Condition C and D, on the other hand, had a 2% and 1% lower bearing force than condition A, respectively. The increased in-between distance and lower interaction between their pressure bulbs resulted in a substantial performance gain.

3.2 Effect of the footing in clayey sands

Condition A has only isolated footing, as illustrated in Figure 7; as a result, the pressure bulb develops with progressive displacement, and the depth of the pressure bulb is the smallest of the four. Because there are multiple footings in Condition B and the distance between them is the smallest, the pressure bulbs interact with one another and generate the largest settlement, despite the fact that the soil profile is similar. To emphasize the distinction between Conditions A and B, the 12 mm settlement layer in Condition B is elevated above the layer in Condition A. The displacement layer for condition C is substantially higher than for conditions A and D, as seen in Figure 9. The pressure bulb of the centre footing interacts with the other two at a higher level since the in-between distance is just 1.5 times the length of the footing. Finally, in Condition D, there are multiple footings, but the distance between them is 2.5 times the length of the footing. As a result, the pressure bulbs of each footing barely interact.

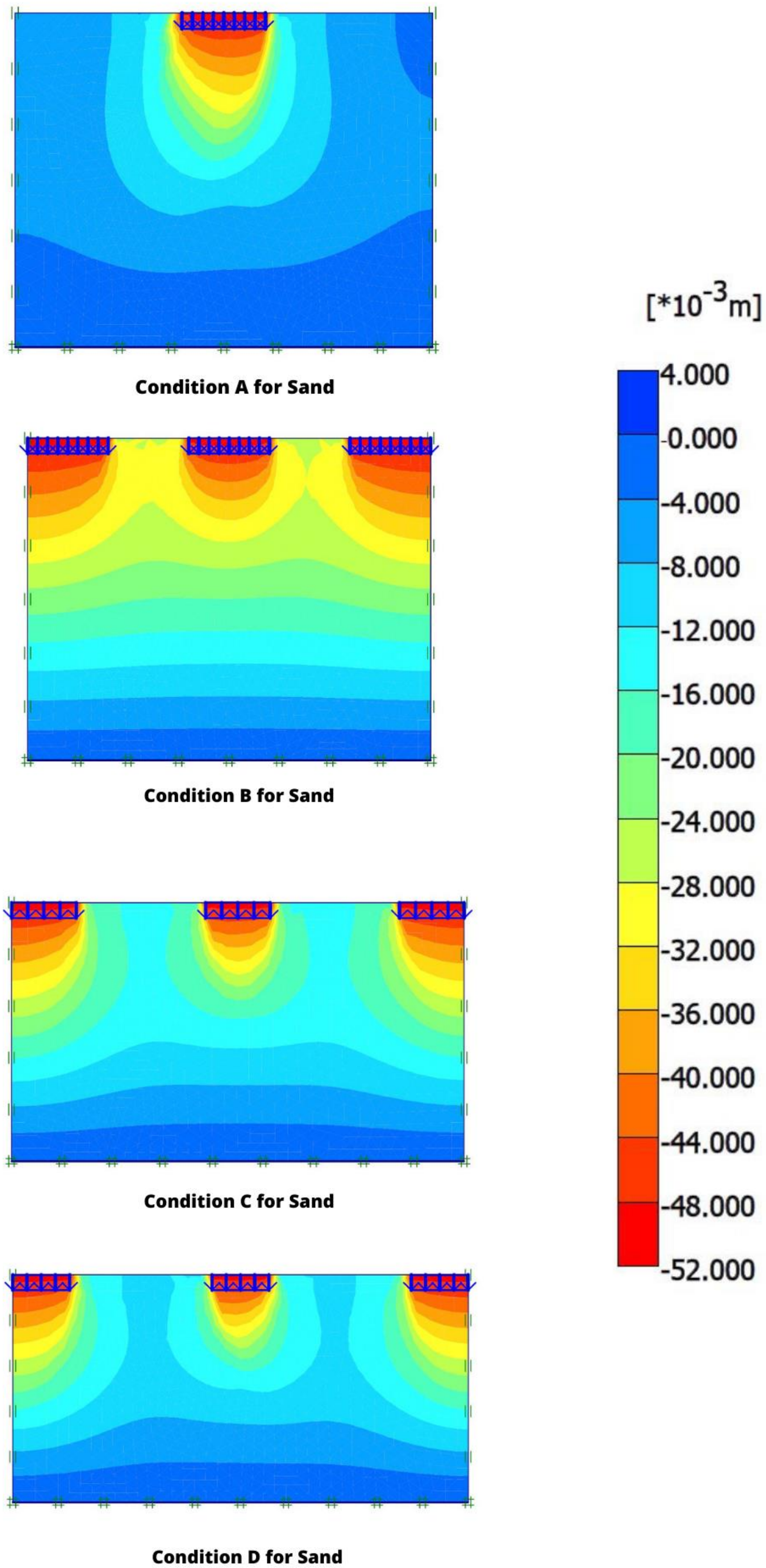

Figure 5: Conditions on Sandy soil from PLAXIS (condition A, B, C, D)

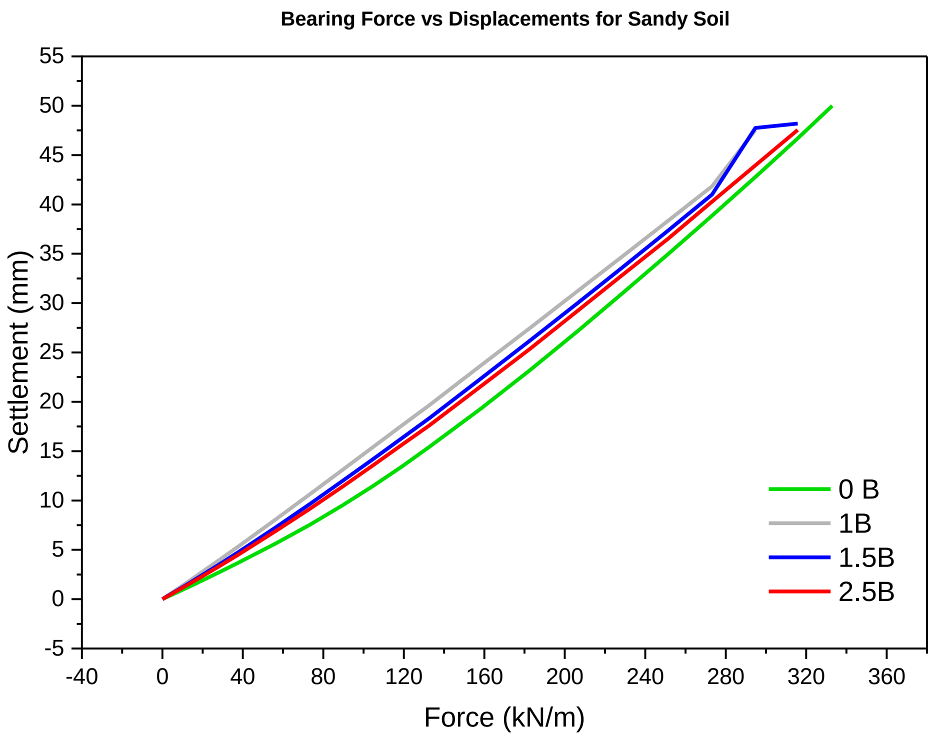

Figure 6: Graph on Bearing Force vs Displacements for Sandy Soil

The bearing force vs. displacement curve for all circumstances at sandy soil is shown in Figure 8. Under condition A, the single isolated footing can withstand 332 kN/m force, which is the maximum bearing capacity for 50 mm settlement. Condition B, on the other hand, found a nearly 9.5 percent lower bearing force than condition A when multiple footing action on sandy soil was examined with the shortest in-between distance. Condition C and D, on the other hand, had a 2% and 1% lower bearing force than condition A, respectively. The increased in-between distance and lower interaction between their pressure bulbs resulted in a substantial performance gain.

3.3 Correlations for sandy soil

For sandy soil with condition A, B, C, D, the force settlement behaviour can be predicted by the equation 1, 2, 3, and 4 respectively and illustrated in Figure 9.
(Soil unit weight varying 17-19 kN/m^3 for below phreatic level, 20-22 kN/m^3 for above phreatic level, modulus of elasticity and friction angle ranging from 12000-14000 kN/m^2 and 27°-31° respectively)

$$d = (1.6657 \times 10^{-4} \pm 5.17 \times 10^{-6})f^2 + (0.0964 \pm 0.00164)f + (-0.1479 \pm 0.0915) \qquad R^2 = 0.9997 \quad (1)$$
$$d = (6.3974 \times 10^{-5} \pm 1.0429 \times 10^{-5})f^2 + (0.1383 \pm 0.0029)f + (0.0472 \pm 0.1426) \qquad R^2 = 0.9994 \quad (2)$$
$$d = (9.9475 \times 10^{-5} \pm 1.4865 \times 10^{-5})f^2 + (0.1252 \pm 0.0044)f + (-0.0488 \pm 0.2337) \qquad R^2 = 0.9998 \quad (3)$$
$$d = (9.5863 \times 10^{-5} \pm 2.9938 \times 10^{-6})f^2 + (0.1214 \pm 8.9431)f + (-0.1184 \pm 0.0470) \qquad R^2 = 0.9998 \quad (4)$$

3.4 Correlations for clayey sand

For sandy soil with condition A, B, C, D, the force settlement behaviour can be predicted by the equation 1, 2, 3, and 4 respectively and illustrated in Figure 10.
(Soil unit weight varying 16-18 kN/m^3 for below phreatic level, 18-20 kN/m^3 for above phreatic level, modulus of elasticity and friction angle ranging from 4000-6000 kN/m^2 and 18°-24° respectively)

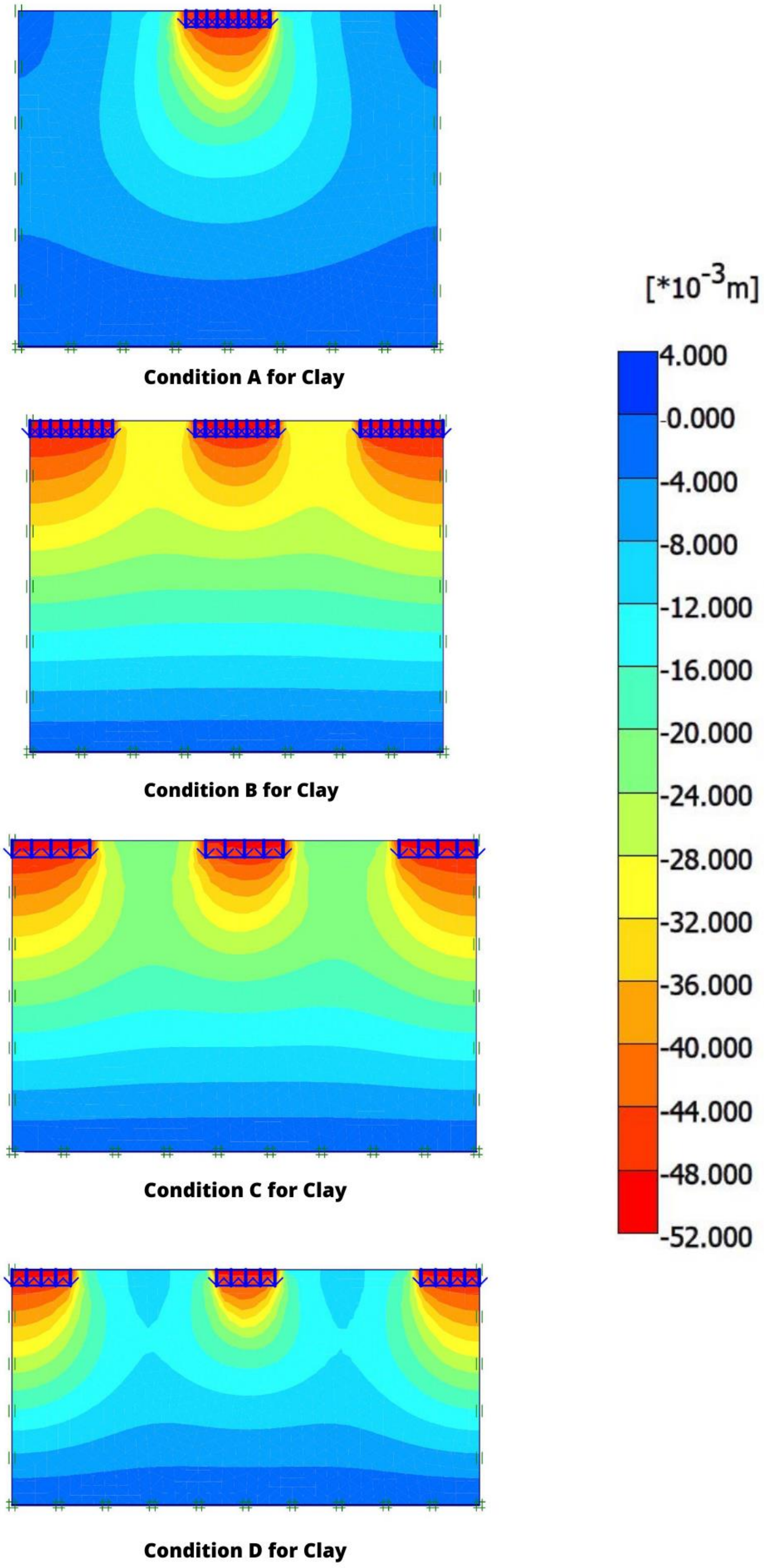

Figure 7: Conditions on Clayey Sand from PLAXIS (condition A, B, C, D)

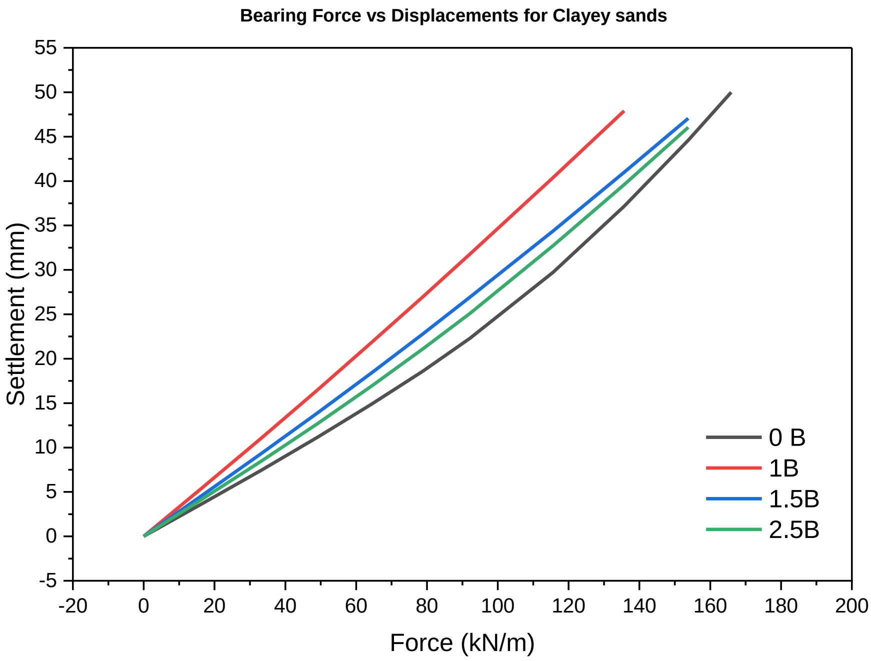

Figure 8: Graph on Bearing Force vs Displacements for Clayey Sand

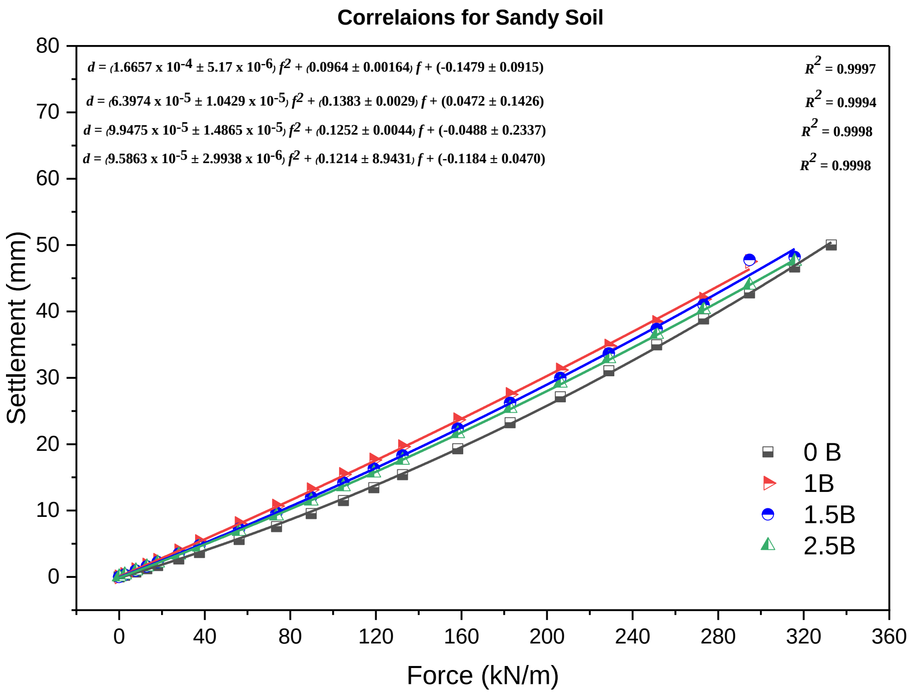

Figure 9: Correlations for sandy soil

$$d = (7.3870 \times 10^{-4} \pm 4.8295 \times 10^{-5})f^2 + (0.1736 \pm 0.0080)f + (0.3612 \pm 0.2651) \qquad R^2 = 0.9993 \quad (1)$$

$$d = (1.9368 \times 10^{-4} \pm 2.8042 \times 10^{-6})f^2 + (0.3268 \pm 3.7326 \times 10^{-4})f + (-0.0010 \pm 0.0099) \quad R^2 = 1.0 \quad (2)$$

$$d = (2.2238 \times 10^{-4} \pm 3.7207 \times 10^{-6})f^2 + (0.2715 \pm 5.6667 \times 10^{-4})f + (0.0259 \pm 0.0171) \quad R^2 = 1.0 \quad (3)$$

$$d = (4.1535 \times 10^{-4} \pm 1.3445 \times 10^{-5})f^2 + (0.2346 \pm 0.0020)f + (0.0881 \pm 0.0620) \qquad R^2 = 0.9999 \quad (4)$$

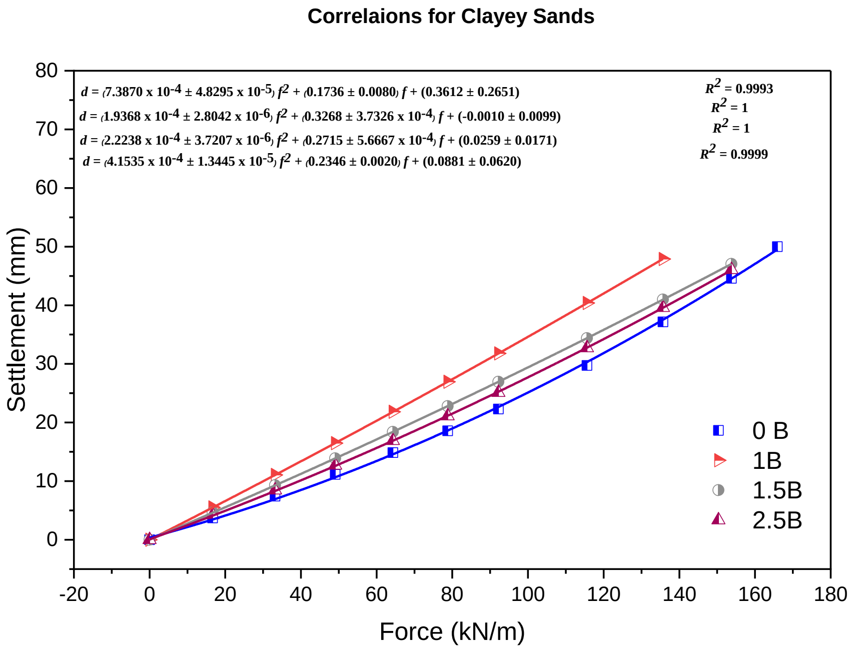

Figure 10: Correlations for clayey sand

3.5 Proof Check

The analytical result was justified by Terzaghi, Peck, and Mesri (1996) ($q_{ult} = CN_c + qN_q + \gamma BN_\gamma$) and Meyerhof (1957) ($q_{ult} = cN_cS_cD_c + gDN_qS_qD_q + 0.5gBN_gS_gD_g$) as it varies 7-9% for Terzaghi's equation and 4-5% for Meyerhof equation. So, it can be said that the procedure was valid. However, only 2D analysis was used in this work for prediction and to generate generalized formulas; as a result, 3D analysis is advised for greater prediction accuracy.

4. CONCLUSIONS

From the analytical investigation the following conclusion can be drawn.

- The isolated footing at Condition-A was able to resist maximum bearing force (332.92 kN/m) at 50 mm settlement for both sandy soil and clay sands.
- Condition-B displayed the minimum bearing force for both the soil condition as the footing was surrounded by multiple footing actions and the pressure bulb was also intersecting at higher elevation.
- The correlation for footing actions for these soil conditions can be used as it was justified by the formula of Meyerhof and Terzaghi equation.
- Finally, to analyse isolated footing surrounded by multiple footing action the reduction of bearing capacity, must be applied.

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