Finite Element Analysis for improving the bearing capacity of Existed strip footings

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Abstract:
Existing foundation is usually subjected to additional loads from different sources like increasing floor number, additional live load and eccentric loads. A result the foundation bearing capacity failure and excessive settlement are exhibited. Consequently, the aim of this work is to predict using a finite element method software (PLAXIS 3D) the reliability of increasing the loaded strip footing bearing area method on increasing the ultimate bearing capacity of the footing and decreasing settlement. The foundation soil used was dense sand (Dr=81%). Numerical analysis are validated by comparing the numerical results with results obtained using various analytical methods by Meyerhof, Hansen and Vesic. The effect of increasing footing size on the bearing capacity factor ($N\gamma$) is studied. Finally, the effect of load eccentricity was studied. It was concluded that ultimate load capacity is increased by as much as 67% in case of increasing footing area by 100% ($\Delta B/B = 1$) with significant reduction in settlement that found to be 37%. As well, it was found that the bearing capacity factor ($N\gamma$) is reduced when the footing size increases which agree with previous works done on this issue. It was found also, that increasing footing area decreases significantly the load eccentricity effect on bearing capacity and modifying the bearing capacity failure from general to punching shear failure.

Keywords:
Strip footing, Sand, Bearing capacity, Settlement, strengthening, eccentricity, numerical analysis

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Introduction:
Although the majority of foundations are properly built and function as intended, there are many situations when soil movement can lead to damage and foundation failure. In addition to the foundation being subjected to high loads, common soil issues that result in foundation failure include heave or shrinkage from expansive soil, consolidation due to soft and organic soil, and movement due to uncontrolled or deep fill (Greenfield and Shen, 1992) [1]. Natural catastrophes like earthquakes (Day, 1994) and fires can negatively affect a foundation [2].

However, there are many well-known and developed methods for strengthening soil. On the other hand, the conditions of the site might occasionally make them unaffordable and unrestrictive. Some circumstances make it challenging to apply them to already-built foundations. (Verma and Char, 1986), (Mahmoud et al., 1988), (Verma et al.,1992), (Mandal, 1995), and (Bahloul et al., 2004) investigated the potential use of vertical reinforcement along either side of an existing footing as a method of soil reinforcement. [3-4-5-6-7]

In order to solve the issue of strip footing on sandy soil next to a slope, (Azzam and Farouk, 2010) used a different method called skirted foundation. The phrase was used to enhance and boost bearing capacity [8].

More recent work done by (Elif Ciceka. Et. al., 2015) they investigated using an experimental model the effect of geosynthetics reinforcements of different lengths on bearing capacity of strip footing on sand soil. While (Noor Ibrahim Hasan. Et. al., 2020) they studied numerically and analytically the effectiveness of geogrid reinforcement on the behavior of strip footings on clayey and sandy soils [9-10].

Other materials like using waste tires shreds-soil mixture beneath foundation was studied by (Gourav Gill. Et. al., 2021) and using Fibers – soil mixture reinforcement was investigated by (M. Mirzababaei. Et. al., 2014) [11-12]

While (Masoud and Ehsan, 2017) used a geotextile soil reinforcement approach to increase the footing's ultimate bearing capability keeping the same area [13]. In order to increase the loaded footing soil system carrying capacity, it is consequently proposed that an alternate strategy be used rather than digging up the site and adding reinforcement. This strategy is based on expanding the contact area beneath the overloaded footing, and there are a variety of ways to strengthen the foundation of a building undergoing reconstruction or of technological equipment. The choice of approach is influenced by factors like the kind of the existing foundation, the effectiveness of it, the engineering-geological stratification characteristics in site, the level of the groundwater table in site, the design of the building, the acting load on the foundation, etc.

On the other hand, the bearing capacity of eccentrically footings with dissimilar sizes and configuration studied by (Nawghare et al. 2010)[14]. The results of unlike footings are compared with focus and eccentric forces. It has been found that as the load is acted eccentrically the bearing capacity sharply reduced based on shape and size of tested foundation. (Nasr and Azzam, 2017) investigated the response of unconventionally eccentric strip footings installed on sand [15]. They carried out experimental and numerical studies to shed the light on the effect of utilizing reinforcing layer beneath the loaded strip footing with different eccentricity. It can be concluded that the using such reinforcement has a great effect on increasing the bearing capacity under different load eccentricity and control settlement.

Based on the above introduced investigation by different researchers, it is acceptable to strengthen a foundation by injecting cement slurry, synthetic resins, etc. if the foundation material is in a poor condition (mechanical failure, the existence of settlement cracks, and cracking of the foundation body). However, if there is no failure occurs in the reinforced concrete footing, it is preferable to enlarge just the bearing area in order to reduce the contact stress in the subgrade layer.

Therefore, the present paper will investigate a strengthening method by increasing the bearing area along each side of loaded strip footing (existing foundation) on enhancing the bearing capacity and reducing associated settlement. Also, it investigates the effectiveness of the mentioned method in case the footing is subjected to eccentric loading too. Finally, the identification of the bearing capacity failure mode under strengthened footing is obtained.

Numerical study:

Numerical Model Description:

A numerical study is conduced utilizing a finite element method commercial computer program package PLAXIS 3D (Brinkgreve, R. B. J., et al. et. al., 2019) [15]. This software is well known for solving various geotechnical engineering problems. The numerical model dimensions as shown in Figure 1 are selected large enough to avoid the boundary effects. The length of the model is 20 times the footings width B, width of the model is equal to 15B and height of the model equals 10 times the footing width B.

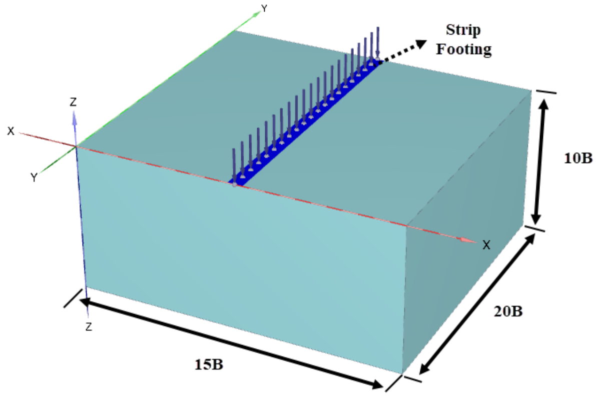

Figure 1: Setup of the numerical model

The soil was modelled using advanced hardening soil model (HS). This model required input of ten parameters including the following: angle of soil internal friction (ϕ), soil cohesion c, angle of dilatancy (Ψ), Primary oedometer load stiffness Eoedref, modulus of elasticity E50ref, unloading-reloading modulus Eurref and power (m). The input parameters of the soil are presented in table 1. According to (Brinkgreve et. al. 2010) [16] the values of Primary oedometer load stiffness Eoedref, modulus of elasticity E50ref, unloading- reloading modulus Eurref and power (m) are estimated using the following formulas:

E50ref= Eoedref= 60000 Dr/100 (kN/m2) (1)

Eeurref= 180000 Dr/ 100 (kN/m2) (2)

m= 0.7–Dr/320 (3)

Where: Dr= Sand relative Density

Table 1: Input parameters used in Hardening soil model

Parameter	Value
Unit weight γ (KN/m3)	18
E50ref (Mpa)	50
Eoedref (Mpa)	50
Eeurref (Mpa)	150
υur	0.2
Angle of Sand internal friction ϕ (°)	39°
Cohesion C (Kn/m2)	1
Dilatancy angle ψ (°)	9°
M	0.5

The footing of reinforced concrete was modelled using the plate element with modulus of elasticity equal to 2.1x107 kN/m^2 and unit weight of 25 kN/m3. The size of mesh used was fine to enhance the calculation results.

Studied parameters and calculation steps:

The parameters investigated are the effect of increasing footing bearing area expressed by ratio (ΔB/B) on ultimate bearing capacity and settlement of footing. Secondly, the effect of footing width of the bearing capacity factor (Nγ) was studied. Finally, the effect of load eccentricity on ultimate bearing capacity of footing with and without strengthening by adding bearing area.

The loading steps or stages used in the numerical analysis program PLAXIS 3D are as following:

- **Initial stage:** the generation of the initial stresses is performed using the K0 procedure in this stage.
- **Construction of strip footing:** in this stage the simulation of footing construction is performed by activating the plate element.
- **Applying 50% of ultimate expected load:** in this stage the simulation of strip footing loading by applying 50% of expected ultimate load.
- **Increasing footing bearing area:** this stage simulates the addition of extra bearing to the footing by activation plate elements.
- **Loading the enlarged footing to failure:** in this final stage the enlarged footing is loaded until failure occurs.

Validation of the numerical model:

The numerical model is validated before starting the test series. The validation is performed by comparing the results of a previous laboratory model done by (EL Siragy, 2019) [18] on strip footing of width equal to 10cm resting on dense sand (Dr=81%). The dimensions of the numerical model are chosen exactly the same as the laboratory model to check the accuracy of PLAXIS 3D software to predict the ultimate bearing capacity. Also, a comparison is performed with analytical method results using (Meyerhof, 1951 and Vesic, 1973) methods is shown in Figure 2 [19-20]. From Figure 2 it is concluded that well known PLAXIS 3D software predicts well the values of ultimate bearing capacity estimated from stress vs settlement curve using 0.1B method. It is concluded that a good concurrence is obtained between FEM, experimental and analytical results. Therefore, the current program is well adopted to investigate and identify the problem under investigation.

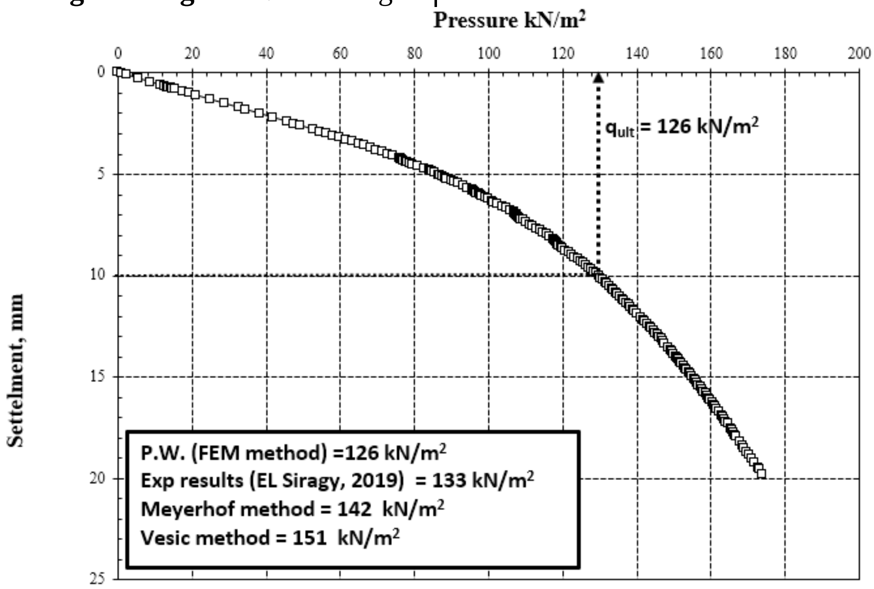

Figure 2: Comparison between FEM, experimental and analytical methods results

Numerical Model Results and Discussion:

Series of tests are conducted on strip footing with varying widths from 1 to 2m before and after loading with 50% of expected ultimate load to investigates the effect of increasing the bearing area on ultimate bearing capacity and settlement of footing. First the tests were done before foundation construction. Secondly, the tests were done on already constructed foundation where addition of area to the footing is investigated on loaded footing with 50% of its expected ultimate load. Figures (2-3) shows examples of plaxis output (deformed mesh and vertical displacement shading) for the case of loading to failure load a strip footing of width = 1m.

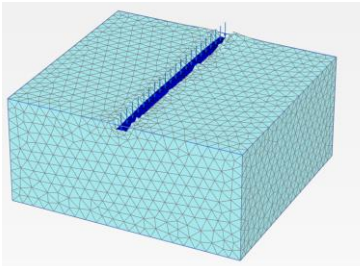

Figure 2: Deformed Mesh

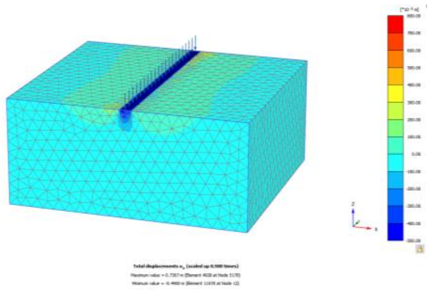

Figure 3: Vertical Displacements

Effect of increasing bearing area before loading the foundation:

In this case as mentioned before a series of loading tests were done to investigate numerically the effect of increasing footing bearing area before construction. Fig. 4 shows the pressure-settlement curves for this case in case increasing footing width with values from 20% up to 100% (ΔB/B = 0.2 up to 1).

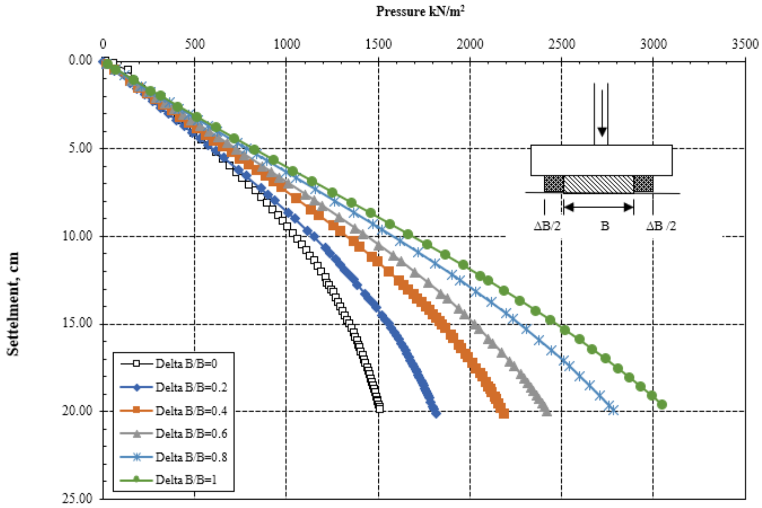

Figure 4: Pressure-settlement relationship for footing improved by addition of bearing area

From Fig. 4 and by using 0.1B method for estimating the ultimate bearing capacity from pressure versus settlement curves it is observed that the ultimate bearing capacity increases with increase of footing area (ΔB/B) as expected. This increase reaches a maximum of about 67% when increasing the footing area by 100%. This increase is associated with a maximum reduction of settlement by 37% for the same stress level as illustrated in Figure 5. Figure 6 illustrates the relationship between the increase in footing bearing area ratio (ΔB/B) and the ultimate bearing capacity (qult). It was found that the effect of increasing foundation bearing area is significant.

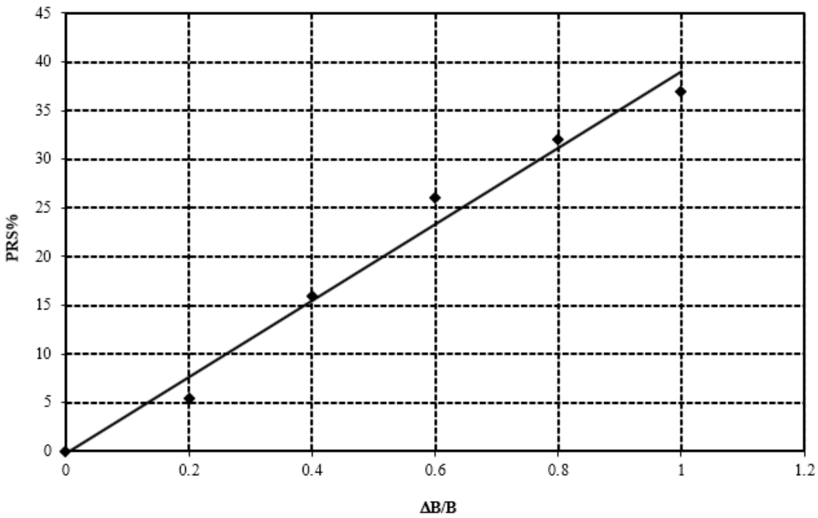

Figure 5: Reduction in Footing settlement percentage (PRS%) versus ratio of footing bearing area increase (ΔB/B)

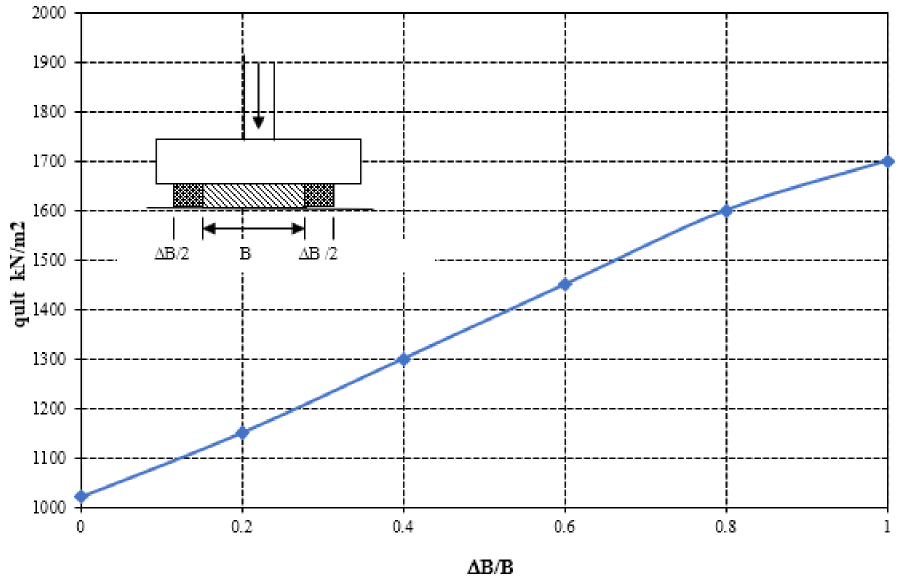

Figure 6: Ultimate bearing capacity vs increasing bearing area ratio

Effect of increasing bearing area for loaded foundation:

In this case a series of loading tests were done to investigate numerically the effect of increasing footing bearing area after construction. Figure 7 shows the relationship between the ultimate bearing capacity values versus the increase of bearing area to initial footing area ratio (ΔB/B = 0.2 up to 1) in case of loaded footing, preloaded footing and computed values of ultimate bearing capacity using (Vesic, 1973) analytical method. It is concluded that the ultimate bearing capacity increases with increase of footing bearing area especially, in case of increasing bearing area of foundation before construction. Also, it was concluded that the ultimate bearing capacity obtained using numerical analysis utilizing PLAXIS 3D software agree with computed values using Vesic theoretical method.

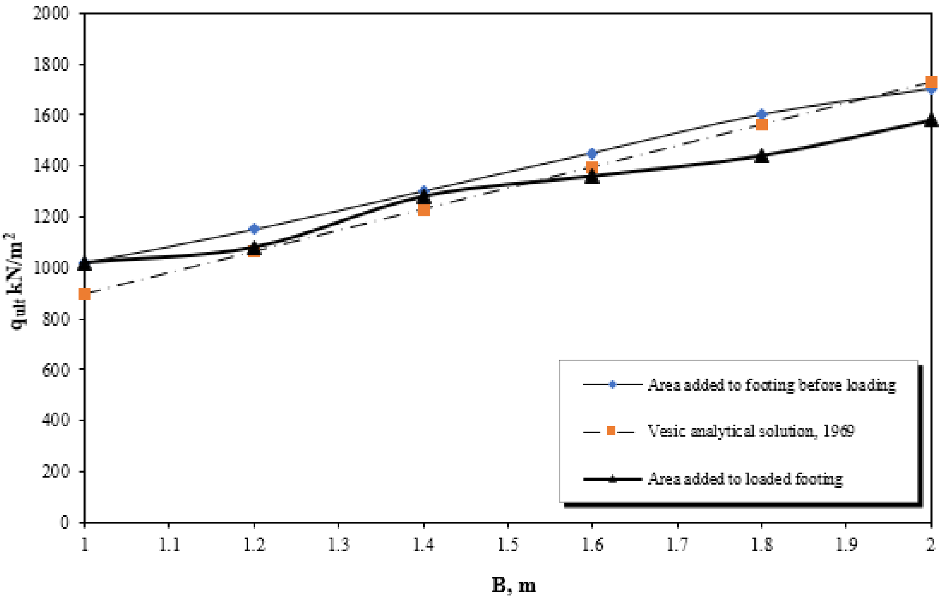

Figure 7: Ultimate bearing capacity vs footing width

Effect of increasing bearing area on bearing capacity factor Nγ:

An investigation of the effect of the footing width on bearing capacity factor (Nγ) was carried out. The bearing capacity factor Nγ is calculated from bearing capacity equation by back calculation (Nγ = qult/0.5γB) where B is the footing width and γ is the soil unit weight. Figure 8 presents a comparison of bearing capacity factor Nγ versus footing width B of current numerical study with those obtained using various methods (Meyerhof, 1951, Hansen 1970, and Vesic, 1973) [19-20-21]. From Figure 8 it was noted that Nγ values decrease with in increase width of footing.

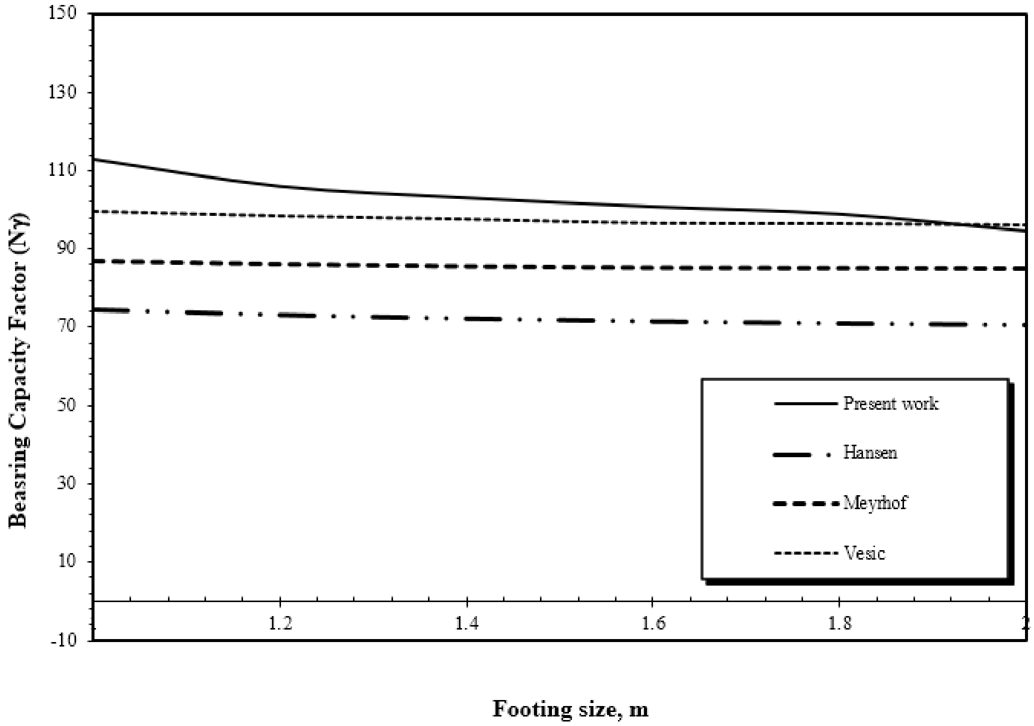

Figure 8: Bearing capacity factor Nγ vs footing width B

Effect of eccentricity:

The effect of load eccentricity is studied using eccentricity ratios (e/B) of 0.05, 0.1 and 0.15.

Firstly, the effect of eccentricity is studied for unstraightened strip footing of width equal to 1m on the ultimate bearing capacity. As shown in Figure 8 it is concluded that with increase of load eccentricity the ultimate bearing capacity decreases as expected.

The effect of eccentricity on strengthened is investigated through studying the relationship between ultimate bearing capacity of a footing subjected to high eccentricity ratio (e/B=0.15) versus the ration of bearing area increase (ΔB/B) as shown in Figure 10. It was found that increasing bearing area improved the bearing capacity of footing subjected to eccentric loading due to increase in contact area which decreases the effect of eccentricity.

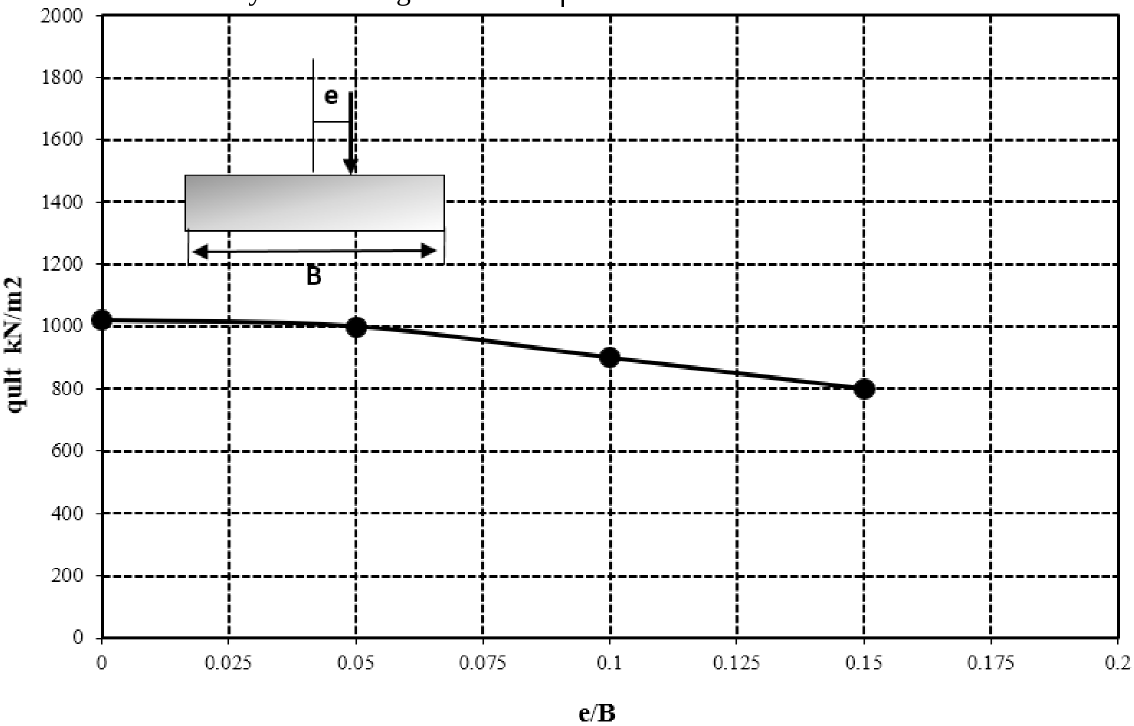

Figure 9: Ultimate bearing capacity vs eccentricity ratio

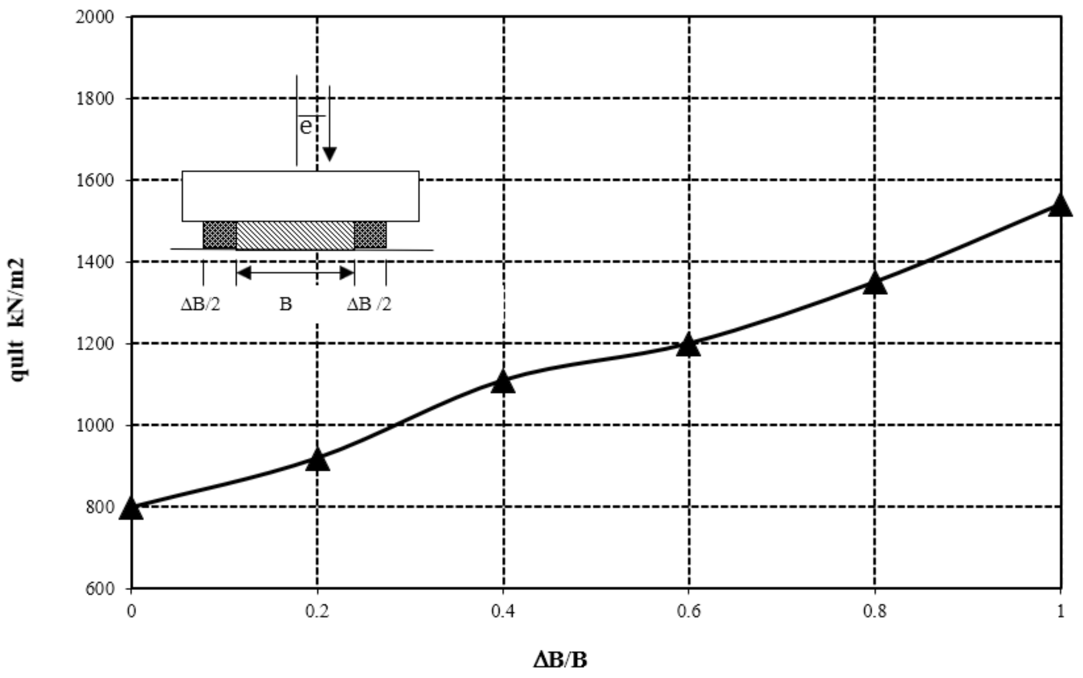

Figure 10: Ultimate bearing capacity vs increase in footing bearing area ratio in case of eccentricity ration (e/B=0.15)

Figure 11 shows the vertical displacement shading for eccentric loaded strip footing. It is observed that the vertical strains are concentrated under the footing in side where load is applied.

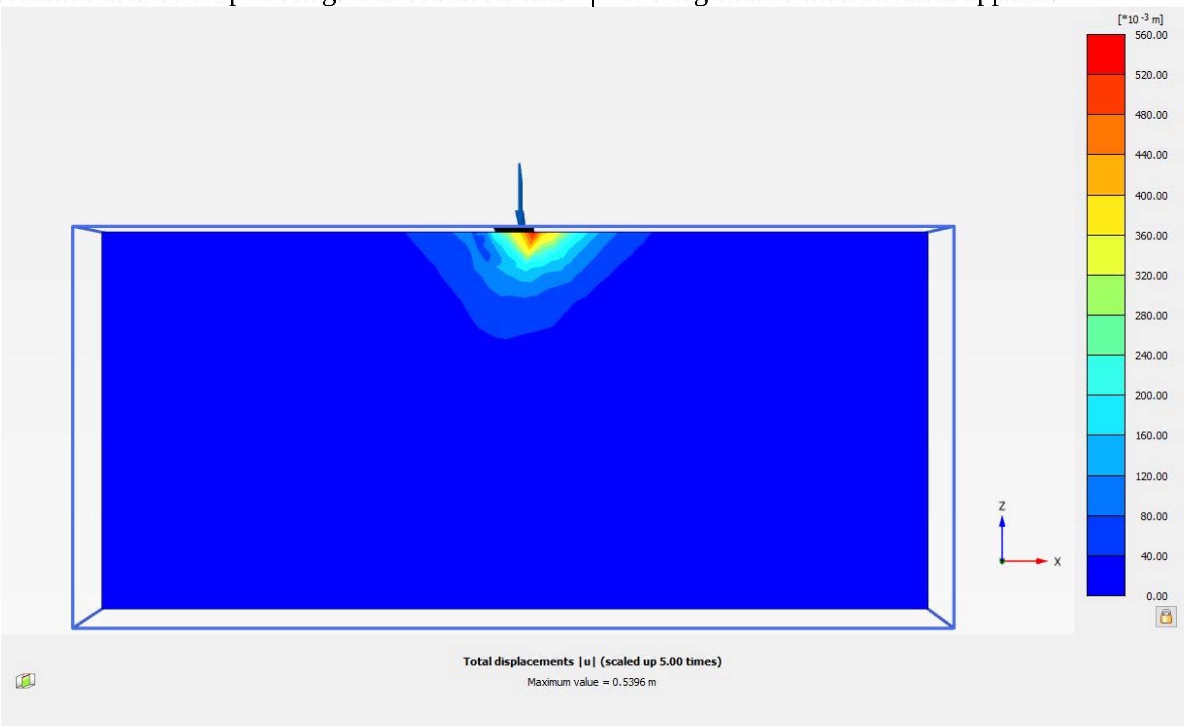

Figure 11: Total displacement shading in case of strip footing with eccentricity ratio e=0.15

Bearing capacity failure MODE:

The shape of bearing capacity failure for strengthened footing on dense sand is similar to failure pattern obtained by (Terzaghi, 1943) [22] as shown in Figure 12. Presenting incremental displacement shading obtained from Plaxis 3D output at failure. Also, Figure 13 presents the total displacement shading at failure. These Figures justified that the addition of such area with native footing is acted as a one unit behaves like on footing with new area as a result the plane of shear failure is modified and stress is decreased. It can be concluded that the normal footing without additional area provided general shear failure while increase the footing area in each side altered the failure mode to be punching shear as confirmed by numerical analysis.

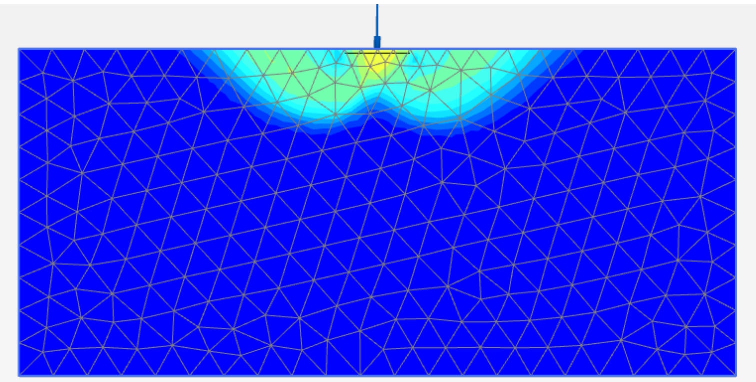

Figure 12: Incremental displacements shading under strengthened footing at failure

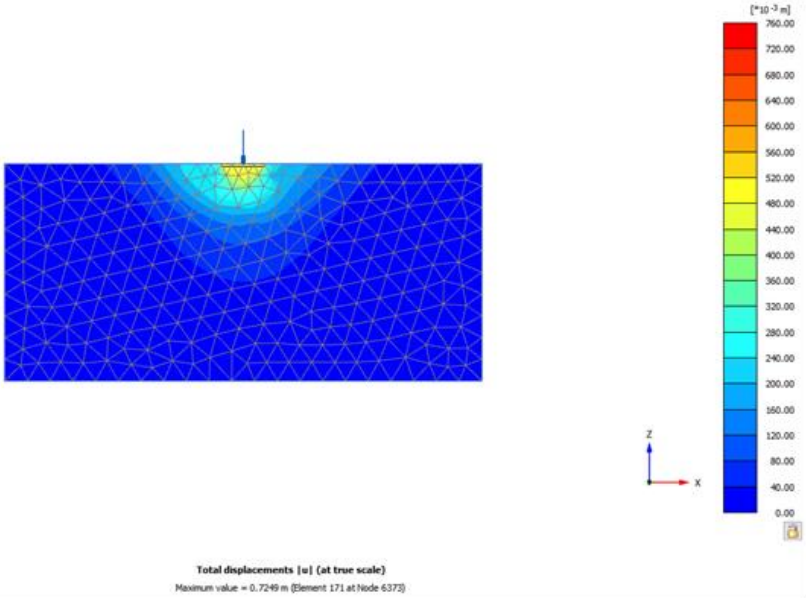

Figure 13: Total displacements shading under strengthened footing at failure

Conclusions:

Based on the numerical analysis results the following are drawn conclusions:

- The method of increasing bearing area under loaded strip footings improves its load-settlement behavior.
- Method of footing strengthening by adding additional bearing area improves significantly the ultimate bearing capacity and reduces settlement.
- The ultimate bearing capacity is improved by a percentage up to 67% for additional area of 100% ($\Delta B/B = 1$).
- The bearing capacity factor ($N\gamma$) decreases with the increase the footing width.
- The percentage reduction in footing settlement (PRS%) is calculated to be up to 37% in case of increasing bearing area by 100% ($\Delta B/B=1$).
- It was found that increasing footing area decreases significantly the load eccentricity effect on bearing capacity.
- The finite element method computer software used in the analysis (PLAXIS 3D) was capable to predict the ultimate bearing capacity failure mode of strengthening strip footing at different cases. It showed that general shear failure diverted to punshing shear failure with limited settlement.

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