



Case Study PLAXIS 2D Model Validation and Numerical, Analytical Comparison Using the Mohr Coulomb and Hardening Soil Models

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(Received: 10 November 2025 Revised: 23 November 2025 Accepted: 05 December 2025)

KEYWORDS

ultimate bearing capacity; PLAXIS 2D; Sensitivity analysis; square footing

ABSTRACT:

Numerical modelling provides an efficient and cost-effective approach for analysing soil behavior under various loading conditions, compared with experimental studies that are time intensive and require a lot of resources. In this study, finite element analyses were performed on local sandy soil to assess the ultimate bearing capacity of square footings with varying widths. The Mohr–Coulomb (MC) and Hardening Soil (HS) constitutive models were employed, and the numerical outcomes were compared with the classical bearing capacity theories developed by Terzaghi, Meyerhof, Hansen, and Vesic. The consequences demonstrate a good level of agreement between numerical predictions and theoretical solutions across both small-scale and full-scale footing dimensions. Furthermore, The Hardening Soil model provides a more realistic depiction of soil behavior and provides closer predictions to theoretical values compared to the Mohr–Coulomb model.

1 Introduction

The maximum load-bearing capacity of the soil (q_u) is the pressure on a footing that causes shear failure, leading to significant settlement. It relies on soil kind, foundation width and depth, water table, loading conditions, and other factors. classical analytical bearing capacity theories proposed by Terzaghi [1] established the first bearing capacity theory based on general shear failure beneath shallow foundations. Meyerhof [2], Brinch Hansen [3], and Vesic [4] subsequently extended this theory by incorporating additional Adjustment factors to account for footing geometry, embedment depth, and load inclination, and foundation slope, thereby enhancing its applicability. These classical formulations form the analytical basis for bearing capacity evaluation and are widely used for comparison with numerical modeling results. This study begins with a theoretical overview of bearing capacity and its analytical estimation using different methods, followed by numerical modeling using PLAXIS 2D. The selection of PLAXIS 2D in this study is attributed to its proven capability in accurately modeling soil behavior and soil–structure interaction through the

Sensitivity analysis of the numerical model. The software provides advanced constitutive models that allow for realistic simulation of nonlinear and anisotropic soil responses under different loading conditions.

In this research, PLAXIS 2D is utilized to analyse the performance of soil foundations under static vertical loading. The software enables the evaluation of stress–strain relationships, deformation behavior, and failure mechanisms of soil systems. Furthermore, the numerical results are compared with classical theoretical solutions to assess the accuracy and reliability of the adopted numerical approach (Brinkgreve ; Obrzud).[5];[6]. Several researchers have employed numerical modeling to investigate the bearing capacity and load–settlement behavior of shallow foundations on sandy soils. Panwar and Dutta [7] used the finite element method with the Mohr–Coulomb (MC) model to study the maximum bearing capacity of rectangular footings resting on layered sand, emphasizing the effects of the upper sand layer thickness and the difference in friction angles between dense and loose sand layers. Lukić Kristić et al. [8]



introduced a combined empirical–numerical approach to predict the load–settlement behavior of shallow foundations on sand, demonstrating the suitability of advanced constitutive models such as the Hardening Soil model. (HS) model in PLAXIS 2D for capturing nonlinear soil behavior. Hussein [9] numerically evaluated the bearing capacity factor N_f for circular and ring footings on sand using PLAXIS with the Mohr–Coulomb model, showing that the radius ratio significantly affects the ultimate bearing capacity, while footing size has a negligible influence. In this case study, the investigation began with numerical analysis of sand soil for six square footings, rather than focusing on a single foundation. These footings varied in size, representing both small-scale and large-scale models. The numerical results were systematically compared with classical theoretical bearing capacity equations to evaluate the precision and dependability of the finite element model. This preliminary modeling ensured that the adopted soil constitutive models, boundary conditions, and interface representations in PLAXIS 2D could accurately capture the behavior of the foundation–soil system.

1.2 Significance of the comparative analysis

Comparative analysis between numerical and theoretical results is essential for assessing the performance and reliability of the adopted numerical model. A close agreement between the approaches indicates an appropriate selection of soil constitutive parameters and boundary conditions in PLAXIS 2D, whereas noticeable discrepancies reveal model limitations and areas for improvement. Consequently, this comparison serves to validate the numerical simulations and enhances the credibility and accuracy of numerical modeling in geotechnical engineering.

2 MATERIAL MODELS AND PARAMETERS

2.1 Soil data

Accurate evaluation of bearing capacity and settlement requires the identification of essential soil parameters, including cohesion and the internal friction angle. These parameters are commonly obtained through a combination of laboratory and in-situ testing. In the present study, fine sand composed of rounded to sub-rounded particles was used. The sand had a specific gravity of 2.6. The measured moisture content and

cohesion were 1.17% and 5 kN/m², respectively. The effective grain size (D_{10}), uniformity coefficient (C_u), and curvature coefficient (C_c) were found to be 0.16 mm, 1.1, and 2.3, respectively. During the tests, the sand exhibited a relative density of 60% and a unit weight of 18.08 kN/m³. A series of direct shear tests were performed at the same relative density, yielding an internal friction angle of 38.6°. All laboratory tests were carried out in accordance with the relevant ASTM standards. This result was used to enter data in to plaxis software. Table 1 show characteristics sand in this study.

Table 1 Sand Properties

Parameter	value	unit
Specific gravity (G_s)	2.6	-
Coefficient of uniformity (C_u)	1.1	-
Coefficient of curvature (C_c)	2.3	-
Dry unit weight (γ)	17.03	(kN/m ³)
Internal friction angle (ϕ)	38.6, 40	(°)
Relative density (D_r)	60	(%)
Water content	1.17	(%)

2.2 Material models

The Mohr–Coulomb (MC) model is commonly used in geotechnical analyses as a first-order representation of soil behavior because of its simplicity and the small number of required input parameters. Its linear elastic–perfectly plastic formulation is characterized by Young’s modulus (E), Poisson’s ratio (ν), cohesion (c), and friction angle (ϕ). and dilatancy angle (ψ). For quartz sands, the dilatancy angle is assumed as $\psi = \phi - 30^\circ$, following Bolton [10]. The MC model is implemented under plane strain conditions using 15-node triangular elements, with soil–reinforcement interaction modeled through interface elements.

The Hardening Soil (HS) model is an advanced elastoplastic constitutive model capable of reproducing nonlinear, stress-dependent soil behavior. Although it shares the same strength parameters as the MC model,



the triaxial secant stiffness at half the peak stress E_{50} , the unloading–reloading modulus E_{ur} , and the one-dimensional compression stiffness obtained from oedometer tests E_{oed} [11,12,13].

2.3 Numerical Model Formation

As an initial step, the numerical model was established to evaluate the ultimate load-bearing capacity and to compare the theoretical predictions with the results obtained from the FEM. The six foundation dimensions were used to establish the geometric configuration of

the FEM model, as presented in Table (2). To ensure accurate representation of soil conditions, this study incorporates a comprehensive set of parameters commonly considered in geotechnical analyses and applies them within the numerical models. Accordingly, the modeling procedure is carried out in four main stages: geometric definition of the soil mass, specification of boundary conditions, assignment of material properties, and selection and implementation of appropriate constitutive (behavioral) models.

Table 2 Small-Scale and Full-Scale Square Footing Dimensions

Model footings (m)		Full scale footings(m)	
A	0.06	D	1
B	0.075	F	1.5
C	0.1	G	2

2.4 Numerical analysis inputs using PLAXIS2D

In the numerical modeling, the soil behavior was defined using the key parameters E_{50} , E_{oed} , E_{ur} , C , ϕ , K_0 , and ν , whereas the footing was characterised by its axial stiffness (EA) and flexural rigidity (EI). A detailed

discussion of these parameters is presented in table (3) ,where their values were determined based on laboratory tests performed on sand Some parameters were obtained or converted through established empirical correlations, and the final adopted values are shown in Table (3)

Table 3 parameters of numerical analysis

Parameter	Mohr coulomb (MC) model	Hardening soil (HS) model
Secant stiffness (E_{50}^{ref})	35000-70000	35000-70000
Tangent stiffness (E_{oed})	-	35000-70000
Unloading/reloading stiffness (E_{ur})	-	105000-210000
Power in stiffness(m)	-	0.5
Cohesion (C)	5, 6.5, 7	5, 6.5, 7
Internal friction angle (ϕ)	38.6°, 40°	38.6°, 40°
Dilatancy angle (ψ)	8.6° , 10°	8.6° , 10°
Poisson's ratio (ν')	0.3	0.3



Reduction factor (Rinter)	0.8	0.8
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3 Result and discussion

3.1 Comparison Between Numerical, Analytical Results

Table (4) and Figure (1) illustrate a comparison of the ultimate bearing capacity values (qu) derived from

numerical analyses using the Mohr–Coulomb (MC) and Hardening Soil (HS) models. and those predicted by classical theoretical methods, including Terzaghi, Meyerhof, Hansen, and Vesic. The results are shown for different footing widths (B), allowing evaluation of scale effects on bearing capacity.

Table 4 compression of numerical and theoretical methods in bearing capacity calculation

B (m)	qu (Numerical)		qu (Theoretical)			
	MC	HS	Terzaghi	Meyerhof	Hansen	Vesic's
0.06	586.95	617.5	572.93	612.86	609.74	616.67
0.075	608.9	622.5	581.98	618.20	614.52	623.05
0.1	619.67	623.24	597.04	627.4	622.50	633.68
1	1092	1100	1139.38	958.58	909.61	1016.47
1.5	1443	1485	1440.68	1142.57	1069.11	1229.13
2	1685.25	1750	1741.98	1326.56	1228.61	1441.79

For smaller footing widths, the numerical results obtained using the MC model show a closer agreement with Terzaghi's bearing capacity theory, while the HS model tends to predict relatively lower values. As the footing width increases, the HS model demonstrates improved agreement with the theoretical solutions, particularly those proposed by Hansen and Vesic. This behavior reflects the capability of the HS model to capture stress-dependent stiffness and nonlinear soil response more effectively at higher stress levels.

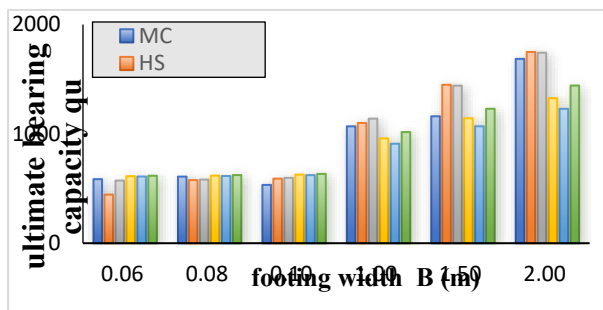
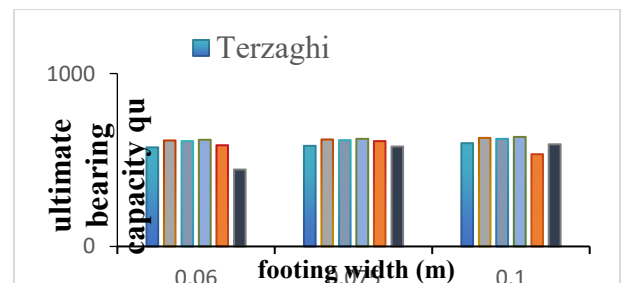
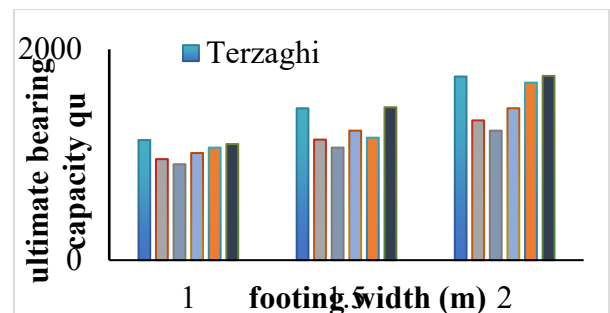


Figure 1 compression theoretical and numerical ultimate bearing capacity for all footings.



(a)



(b)

Figure 2 Compression Between Theoretical Bearing Capacity and Numerical Value Footing a) For Small Scale b) full scale.



The comparative curves illustrate that all methods exhibit a consistent increasing trend of bearing capacity with footing width. However, noticeable differences exist between numerical and analytical predictions, especially for larger widths, where classical theories tend to yield more conservative or scattered results. Overall, the close correspondence between numerical and theoretical results confirms the validity of the adopted numerical models, while the observed deviations highlight the influence of constitutive modeling and soil stiffness representation on bearing capacity predictions.

3.2 Comparison Between MC, HS Numerical, Results

For the smaller foundation widths ($B = 0.06, 0.075, 0.1$ m), the MC and HS numerical results closely match the theoretical predictions, particularly those of Meyerhof, Hansen and Vesic' s. This indicates that both constitutive models can reliably capture the bearing capacity behavior at small scales.

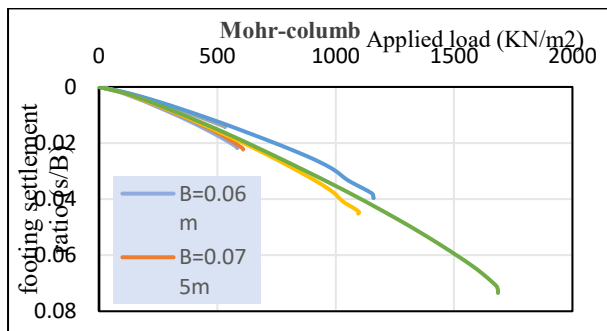


Figure 3 applied pressure - s/b of footings scale for MC model

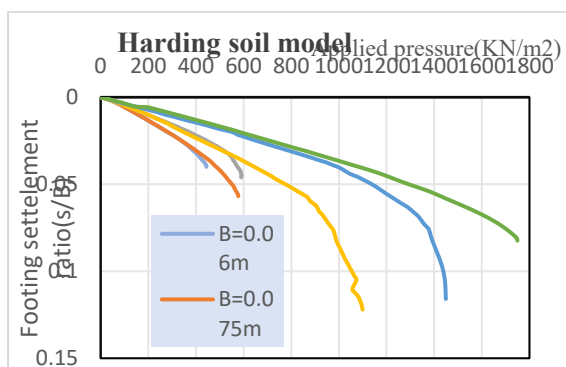


Figure 4 applied pressure - s/b of footings scale for HS model.

For the larger foundation widths ($B = 1, 1.5, 2$ m), the numerical results from both MC and HS again align well with the theoretical methods, especially Terzaghi and Meyerhof equations. This consistency demonstrates that the numerical models remain valid across a broader range of footing sizes and continue to reflect the expected trends in bearing capacity with increasing width.

Figures 3 and 4 show the relationship between applied pressure and the normalized settlement ratio (s/B) for various footing widths, as obtained using the Mohr–Coulomb (MC) and Hardening Soil (HS) models. In both models, settlement increases nonlinearly with applied pressure, reflecting the progressive development of soil deformation under loading.

For small footing widths, both models predict relatively low s/B values, indicating limited scale effects and a confined stress distribution beneath the foundation. In this range, the MC model provides acceptable predictions, while the HS model exhibits slightly stiffer behavior due to its consideration of stress-dependent stiffness.

As the footing width increases, higher settlement ratios are observed, particularly in the MC model, which predicts significantly larger s/B values at higher pressure levels. This behavior highlights the limitations of the MC model in representing stiffness degradation and nonlinear soil response. In contrast, the HS model shows smoother and more controlled settlement curves, demonstrating improved numerical stability and closer agreement with theoretical expectations.

Overall, the comparative results confirm that while the MC model is suitable for preliminary analysis and smaller footing sizes, the HS model provides a more reliable representation of settlement behavior for larger foundations and higher applied pressures, where nonlinear soil behavior and scale effects become more pronounced.

3.3 Sensitivity analysis of the numerical model

Sensitivity analysis is the process of evaluating how the output of a numerical model responds to variations in input parameters such as mesh size, boundary conditions, material properties, and applied loads. Conducting sensitivity analysis helps identify the most influential parameters, thereby improving the quality



and accuracy of the results, enhancing the design and decision-making process, and reducing computational effort. In this study, The sensitivity analysis aims to identify the optimal boundary dimensions of the numerical model, as well as the appropriate number of elements, and to assess the effects of Young' s modulus, cohesion, and friction angle. The sensitivity analysis for these parameters was performed using the PLAXIS calculation program to identify the parameters that most significantly influence the bearing capacity. As shown in the following figures

1- Effect of Number of Elements:

In PLAXIS 2D, higher-order 15-noded elements capture failure mechanisms more accurately and provide greater robustness in geotechnical analyses, although they require longer computation times compared to 6-noded elements. Therefore, an appropriate balance must be achieved between the number of elements, computational effort, and the required level of accuracy. PLAXIS 2D offers five mesh categories: very coarse, coarse, medium, fine, and very fine. A very coarse mesh fails to capture key soil responses, whereas an excessively fine mesh may introduce numerical errors and significantly increase computation time. Consequently, a mesh convergence (sensitivity) study is essential to determine the optimum mesh configuration for each simulation. In this study, a finer mesh was adopted near the square footing, transitioning to a coarser mesh with increasing distance from the loaded area to ensure both accuracy and computational efficiency, sensitivity analysis is shown in Figure 5.

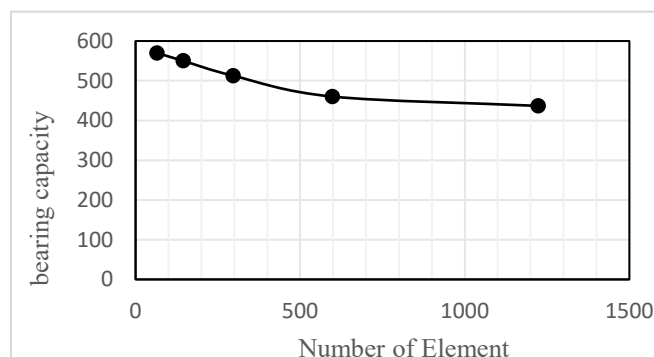


Figure 5 sensitive analysis of bearing capacity by different element numbers.

2- Effect of boundary geometry

In PLAXIS 2D, the geometry of the boundary is essential for accurately representing the interaction between the geotechnical model and its surrounding environment. These boundaries control how the model behaves at its edges, ensuring that external constraints and influences are realistically simulated. To verify the adequacy of the selected boundary dimensions, a sensitivity (or convergence) analysis is recommended by systematically varying the model boundaries and observing their influence on the numerical results. If the outcomes remain stable and show minimal variation as the boundary size increases, the chosen dimensions can be considered appropriate for the simulation. Figure 6 illustrates the sensitivity of the model to boundary geometry.

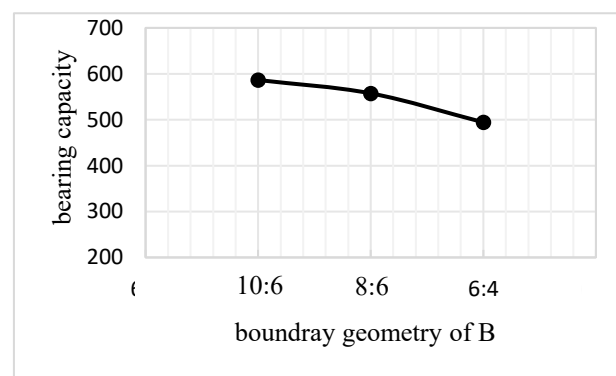


Figure 6 the sensitivity of the model to boundary geometry.

3- Effect of cohesion

Cohesion represents the component of soil shear strength that is not related to friction and remains independent of the applied normal stress. It plays a vital role in enhancing the bearing capacity of soil, as higher cohesion values reflect improved soil strength and a greater capability to sustain applied loads. The sensitivity analysis indicates a noticeable response to changes in cohesion; when cohesion increases from 4 to 7 kPa, a clear improvement in the soil' s load-bearing behavior is observed, resulting in an upward trend of the bearing capacity curve. This increase in cohesion leads to higher shear strength, which in turn enhances the maximum bearing capacity of the footing. As illustrated in Figure 7, variations in soil cohesion have a direct and substantial influence on the ultimate bearing



capacity, confirming the importance of cohesion in overall foundation performance.

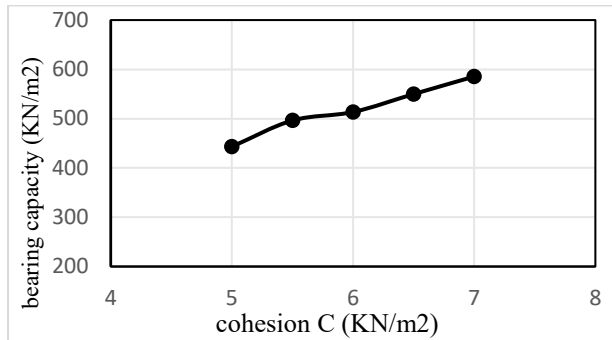


Figure 7 the effect of variation cohesion of soil on the ultimate bearing capacity.

4- Effect of soil Unit Weight

In conducting sensitivity analyses of the ultimate bearing capacity (q_u) of foundations, particularly those resting on sandy soils, it is customary to vary the unit weight of the sand to evaluate its influence on foundation performance. This approach enables the assessment of the degree to which the bearing capacity responds to changes in soil density, therefore providing insights into how fluctuations in unit weight may affect the overall stability and safety of the foundation system. The unit weight of the sand was varied between 16 and 18.5 kN/m^3 to investigate its influence on the maximum bearing capacity. The results, as shown in Figure 8, indicate that q_u increased from 18.4 to 65.3 kPa. However, beyond approximately 17.5 kN/m^3 , further increases in unit weight had only a marginal influence. For the numerical analyses, a unit weight of 17.03 kN/m^3 was adopted.

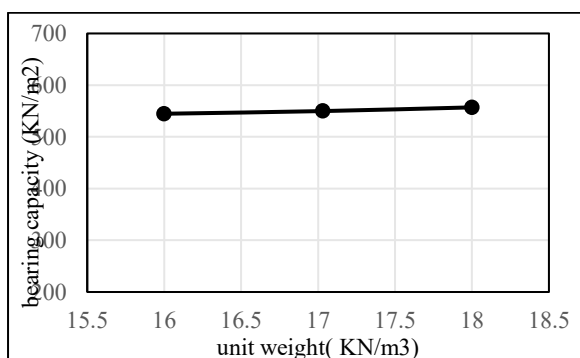


Figure 8 Influence of variations in soil unit weight on the ultimate bearing capacity

5- Effect friction angle

The friction angle is identified as a critical input parameter that significantly influences a model's output, figure 9 demonstrates that the internal friction angle (ϕ) has a substantial effect on the ultimate bearing capacity (q_u). An increase in ϕ leads to higher q_u values, with the effect being more pronounced at larger ϕ . Conversely, q_u decreases when the minimum value of ϕ is considered.

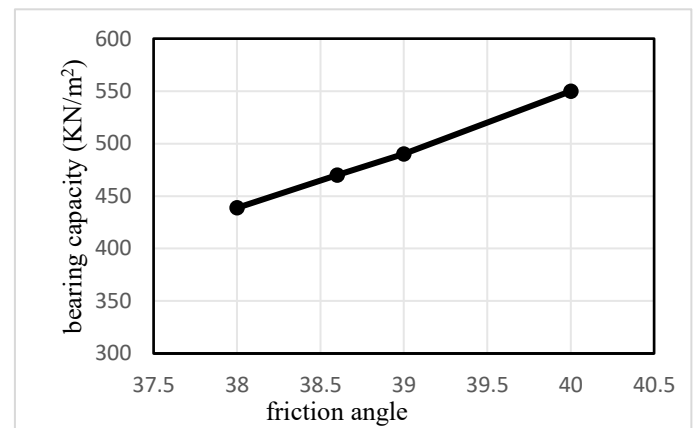


Figure 9 Influence of the soil internal friction angle on ultimate bearing capacity

Effect of Young' s Modulus

Sensitivity analysis of Young' s modulus (E) in sandy soils generally shows that variations in density and grading can lead to significant changes in soil stiffness, often resulting in dense sands exhibiting modulus values up to an order of magnitude higher than loose sands. However, in the current study, the effect of E on the behaviour of the tested dense sand was found to be relatively limited. Despite being poorly graded, the sand contains a measurable amount of silt, which contributes to a moderate stiffness level, yielding Young' s modulus values in the narrow range of 67,000 to 70,000 kPa. This narrow variation indicates that the soil response is not highly sensitive to changes in E under the examined conditions. figure 10 depicts typical variation of bearing capacity with young' s modulus of soil.

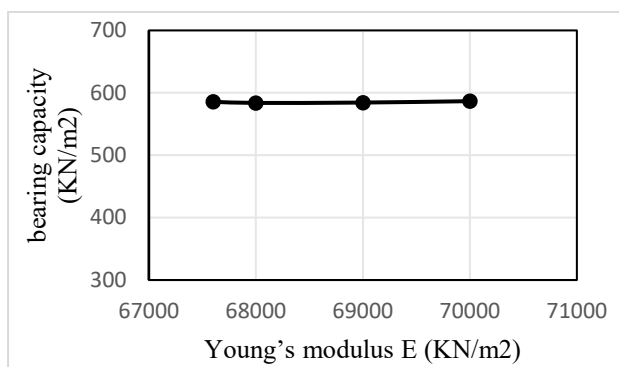


Figure 10 the effect of Young' s modulus of soil on ultimate bearing capacity.

Conclusion:

- Based on the finite element analyses performed on square footings of varying dimensions resting on sandy soil, the following conclusions can be drawn:
- The Mohr–Coulomb (MC) model provides reasonable predictions for small to moderate footings but shows noticeable deviations for larger foundations and higher loads, indicating its limitations in capturing nonlinear soil behavior.
- The Hardening Soil (HS) model demonstrates better agreement with theoretical predictions and more accurately represents scale effects, stress-dependent stiffness, and settlement behavior, making it more suitable for larger footings and higher applied pressures.
- Scale effects become more significant with increasing footing size, as deeper plastic deformations occur. the MC model may be suitable for preliminary analyses and smaller foundation sizes, the HS model is more appropriate for detailed settlement evaluation under higher loads and larger footing dimensions.
- Sensitivity analysis indicates that cohesion and the friction angle are the most influential soil parameters, while unit weight has moderate impact and Young' s modulus shows limited effect. This confirms the robustness of the adopted model parameters and supports the credibility of the numerical results.

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