Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Numerical Study of Bearing Capacity under Strip Footing having Underground Void

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Abstract
This study presents the numerical study of the bearing capacity of the strip footing with an underground void, which was investigated using the finite element method. The study mainly focuses on the effect of the underground void's location on the footing's bearing capacity. For this purpose, numerical solutions for various geometrical parameters were investigated using plain strain finite element analysis. The soil model was assumed to follow the Mohr-Coulomb failure criteria. The result of the void is only visible when the void is above the critical depth. For the present study, the critical depth is five times the width of the foundation. When the depth decreases, the bearing capacity decreases, but the rate is not constant. Moreover, the bearing capacity also increases when the horizontal offset increases for a specific depth. Maximum influence occurs when the void is close to the footing, and the influence decreases when the offset increases. In the present study, the maximum influence distance is two times the width of the foundation of the depth of foundation width(B).

Keywords
Void, Bearing Capacity, Finite Element Analysis, Strip Footing

1. Introduction

The presence of an underground void cause adverse effect on the engineering problem. Such effect includes foundation instability, differential settlement, or even structure collapse. The underground voids are formed due to several reasons. Natural factors that cause the underground void are the dissolution of water-soluble material like limestone and calcareous sediments, differential settlement of municipal solid waste, and settlement of localized lens of compressible soil. In contrast, anthropogenic factors include mining, Tunneling, and subway excavation. Calcareous sediments are widely spread throughout the tropical and sub-tropical regions [1]. Such sediment often consists of voids of several sizes due to the dissolution of limestone and dolomite in the direction of the flow of water [2].

Several studies have been reported on the performance of the footing above void. The first ever study was conducted in 1983. [2] studied the effect of circular and rectangular voids in silty clay experimentally with test soil and test model footing and theoretically using the finite element method. [3, 4] studied the effect of underground voids in clay. They developed a relationship between bearing capacity with depth and eccentricity of void for square, circular shapes. [5] studied the effect of void for double-layered clayey soil. The study found the effect of strength ratio and top layer thickness on the performance of the footing along with the void location with respect to depth of bedrock. [2] studied the effect of multiple voids numerically using 2D Plaxis. The result showed that the failure zone is formed toward the nearest void and extends to other voids if the void is within the influence zone. [6] conducted a model test to analyze the bearing capacity and the failure modes. According to [6], there are three types of failure modes: (a) bearing capacity failure without void failure,(b) bearing capacity failure with void failure, and (c) void failure without bearing failure.Moreover, if voids are present in the series configuration, the effect of lower void does not affect the bearing capacity. [7] studied the effect of the inclination of load in the undrained bearing capacity, which concluded the effect of location, geometry, and number of voids. [8] utilized the Finite element limit analysis(FELA) for undrained stability of strip footing in two-layered clays with variable strength ratio. Based on the result, a design chart and equations have been developed from finite element limit analysis. [9] utilized Finite Element limit analysis (FELA) for the examination of the bearing capacity of strip footing on rock masses with single and multiple voids. The study concluded the effect of void location and mechanism of collapse as (1)roof and wall combined failure,(2) bearing failure without void failure, and (3) roof failure. [10, 11] also used finite element limit analysis(FELA) for analysis of the effect of eccentric load on clay and rock mass respectively. [11] utilized Random adaptive finite element limit analysis(RAFELA)to examine the effect of soil spatial variability on bearing capacity and failure probability of the footing-void system. [12] examined the strip footing on sandy soil above the void. The study produced Bearing Capacity Ratio and efficiency factor to determine the effect of the voids on bearing capacity.

2. Study Area

Pokhara lies in the sub-tropical region of central Nepal. Pokhara Valley is formed by the large volume of layered clastic deposits which is brought from the Annapurna range due to several landslides and debris flow throughout the history of time [13]. Karst structures like subsurface flow channels and underground soluble voids are common in the Pokhara Valley.

These structures are formed due to the dissolution of calcareous material in the clastic layer. The amount of calcareous material varies from 25% to 65% by volume [14]. Karst Structures pose a serious threat to structures like buildings, roads, etc. Such an incident occurred in Pokhara when the highway bridge collapsed at the Seti River [15]. The effect of void on the Pokhara geology has yet to be well covered or unavailable in the literature. However, the effects of void can be seen in different periods, such as the formation of sinkholes or excessive settlement of roads and buildings. For this reason, it is essential to study the effect of underground void on the bearing capacity. This study aims to evaluate numerically the bearing capacity of strip footing above underground void for different locations.

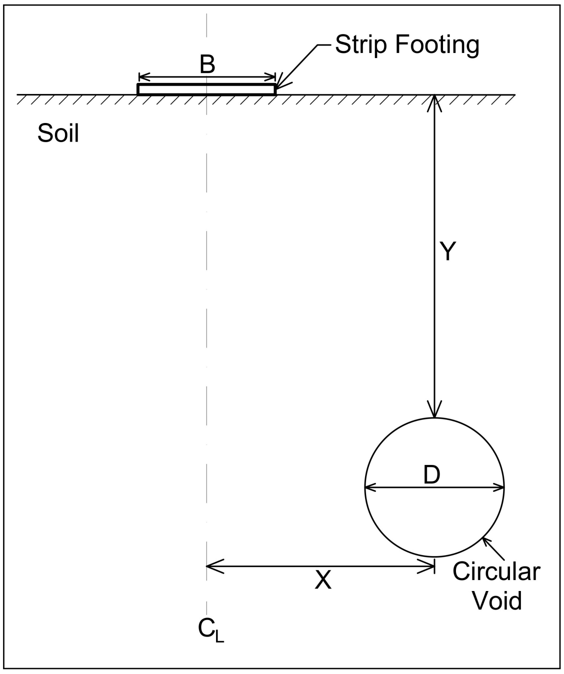

Figure 1: Typical Plain Strain model of strip foundation with underground void

Table 1: Material Property of Soil

Parameters	values
unit weight of soil(kN/m^3)	18(kN/m^3)
Friction angle of Soil,ϕ	34 °
Young's modulus of elasticity(MN/m^3)	14.6 (MN/m^3)
Poisson's ratio	0.25
Dilatancy angle	4 °
Cohesion	70 (kN/m^2)
Failure Criteria	Mohr-Coulomb
Type of material model	drained condition

3. Material and Methods

Commercially available Plaxis 2D version 22 was employed for the analysis of the footing. The plane strain finite element model was developed to simulate rigid strip footing as shown in Figure 1.The void direction is limited to the paralled direction only for this study. The soil was modeled as 15-node triangular elements, whereas the footing is modeled as six-node triangular plate elements. Mohr-Coulomb failure criterion, the ideal elastic-perfectly plastic constitutive model, was used as the constitutive model for the simulation of soil behavior because the current study primarily focuses on the bearing capacity for which Mohr-Coulomb is mostly sufficient [16].The footing is assumed to be rough and lies on the surface without any Embedment depth. A typical model with void is shown in Figure 2.

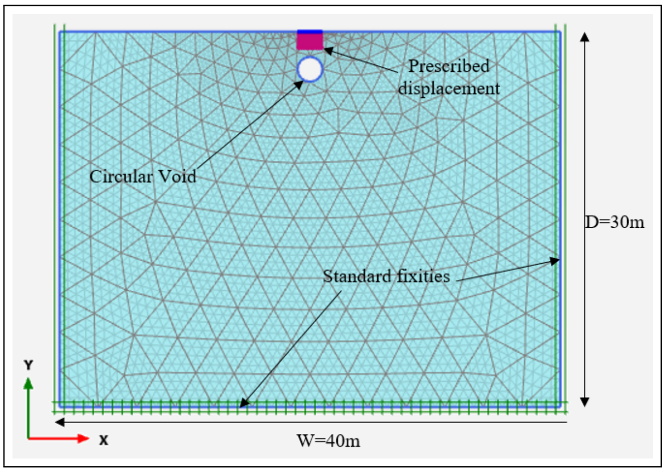

Figure 2: Typical finite element mesh model.

The boundary conditions were fixed by referring to different literature [2, 17, 11, 8, 18]. The horizontal and vertical boundaries are kept at 20B and 15B, where B is the width of the footing. The vertical boundary was fixed by vertical roller support, i.e., only vertical displacement is allowed, and the bottom of the model is fixed in both horizontal and vertical directions. The void was modeled as a tunnel without any lining.To examine the mesh dependency on the failure load, the trail models were analyzed with five cases of mesh options available in Plaxis 2D. Medium mesh with the coarse factor for footing as 0.05 and 0.7176 for the opening is found to be sufficient to capture the bearing capacity. The load was applied to the model through prescribed displacement.

Table 2: Material Property of foundation

Parameters	values
Normal Stiffness(EA) kN/m	3×10^7
Flexural Rigidity(EI) $kN/m^2/m$	2×10^4
Equivalent Thickness,m	0.2
Poisson's Ratio	0.1

The material model used for the FEM analysis is listed in table 1. The value is derived from the correlations from the SPT value extracted from the geotechnical report of the Pokhara, Lamachaur area. As previously mentioned, Pokhara consists of calcareous sediments; hence, a cohesion value of 70 kN/m2 is adopted as the value of cohesion.Since calcareous sediments (especially sand) can reach up to 320 kN/m2 [19]. The property of the footing is consulted from [2]. The value of the material property for footing is illustrated in Table 2.

The geometrical properties of the model are given in Table 3. The horizontal offset or eccentricity of the void is varied from 0 to 4B, whereas for the depth, the value is varied from B to 6B.

4. Research Validation

To assure the accuracy of the FEM model, the bearing capacity obtained is compared with previous study [2]. [2] studied the effect of single as well as multiple voids on the calcareous sediment in the Okinawa region in Japan. The summary of the comparison is shown in Figures 3 and 4.

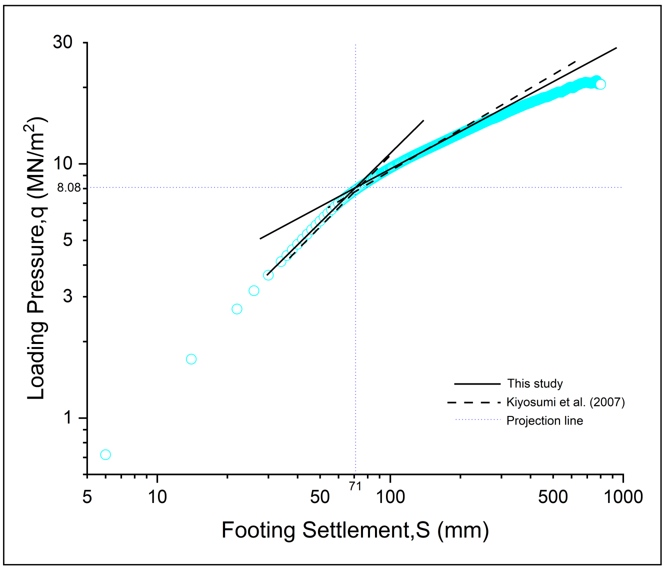

Figure 3: Relation between loading pressure and footing settlement for no void.

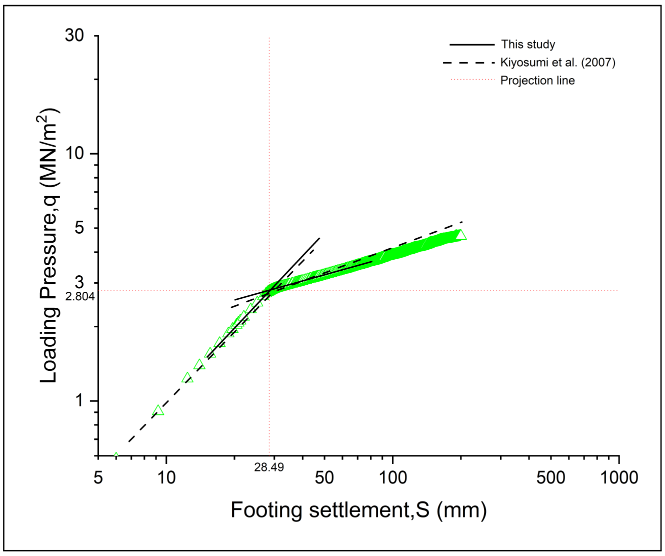

Figure 4: Relation between loading pressure and footing settlement for void.

The results are remarkably similar to that from [8]. For the non-void condition, the value of bearing capacity is 8.08 MN/m2 in this study, whereas from the previous study, it was 7.8MN/m2, and for the void cases, the value is 2.804 MN/m2 and 2.8 MN/m2 respectively for this study and previous study. Hence, the results are close in both cases.

5. Results and Discussion

Numerical solutions in the form of load settlement curves for a range of geometrical parameters stated in Table 3 were obtained from finite element analysis. The load settlement curve is plotted in a log-log plot to find the yielding pressure. The outcome of an FE simulation that displays the settlement and displacement characteristics of the soil, as well as the shear straining of the soil brought on by the application of load, allows one to witness the deformation of the soil beneath the foundation.

Table 3: Geometrical Parameters

Geometrical Parameters	values
width of footing(B)	2m
Width of analysis soil (W)	20B (40m)
Depth of analysis soil (D)	15B (30m)
Shape of Void	Circular
Size of Void (D)	2m
Vertical position of void (y)	B, 2B, 3B, 4B,5B, and 6B (from the base of the footing to the crest of the void)
Horizontal position of void (x)	0B, 1B, 2B, 3B, and 4B (from the center of the foundation to the center void)

5.1 Effect of position of void

To perform parametric analysis, 30 FE model has been simulated, varying the position of the void in horizontal as well as in vertical direction.

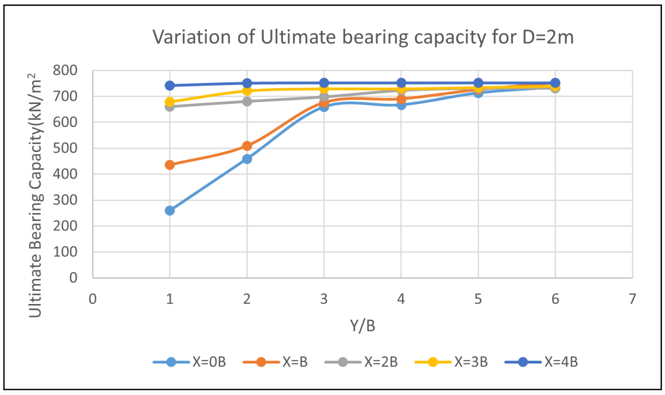

Figure 5: Bearing capacity of foundation with circular void with variation of void depth(y) for different horizontal offset(x).

5.2 Effect of the void depth(y)

Figure 5 shows the variation of bearing capacity with the depth of void from the foundation. When the void is present just below the footing, the reduction of the bearing capacity can be seen to be maximum. With the increase in the depth of the void, the effect gradually decreases, and the effect diminishes when the width of the foundation(B) to void depth ratio is greater than 5. This shows that y/B=5 is the critical depth for the circular void with a diameter equal to 2m. Below this level, there is no influence of void on the bearing capacity of the soil. Moreover, the effect of the presence of the void also differs for different horizontal offsets of the void.

Hence, the result sheds light on the presence of the critical depth for the void, which affects the bearing capacity when the void is present to avoid this depth.

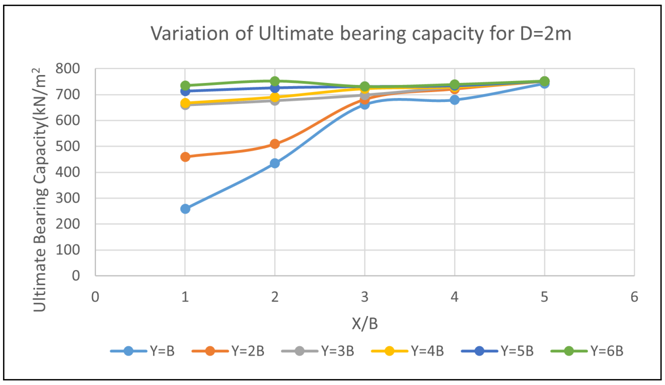

Figure 6: Bearing capacity of foundation with circular void with variation of Horizontal offset(x) for different void depth(y).

5.3 Effect of horizontal offset of the void(x)

A series of x/B graphs is presented in Figure 6 to comprehensively research the void's horizontal position. It can be seen that when the void goes away from the footing, the greater the bearing capacity becomes. maximum deduction of bearing capacity occurs when the void is below the footing. The deduction is nearing about 65% for the void at depth B from the base of the footing with no offset. When the x/B ratio is greater than 3, the effect of the horizontal offset diminishes, indicating that 3 is the critical zone for the horizontal direction for the circular void of 2m diameter.

The study shows that the vertical depth is more critical than the horizontal depth as the effect in the horizontal direction seems to diminish faster than in the vertical direction. Hence, the presence of a circular void in the region y/B greater than five and x/B greater than two do not affect the bearing capacity

6. Conclusions

In this study, the behavior of strip footing due to underground void has been studied Numerically. Moreover, the critical zone of the void has been discussed. Some of the Major conclusions derived from the current study are.

- The presence of an underground void adversely affects the bearing capacity of the soil. The magnitude of bearing capacity is greater for soil without voids than with voids.
- The presence of the void at a depth greater than or equal to five times the foundation width does not affect the bearing capacity. Hence, the effect of void is eliminated.
- The presence of the void at the horizontal offset greater than two times the foundation width has very little interference with the bearing capacity.

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