# Assessing the Effect of Underground Void on Strip Footing Sitting on a Reinforced Sand Slope with Numerical Modeling

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**Abstract-This paper presents the results of the numerical analysis undertaken to investigate the effect of the underground void on the load-bearing capacity of a strip footing placed on an unreinforced and geogrid-reinforced sand slope with a void inside. The failure mechanism of the soil was also investigated. The numerical model was obtained using 2D plane-strain FEM analysis (in Plaxis software), in which the nonlinear Mohr-Coulomb model was utilized. The effects of various parameters such as the number of geogrid layers (N), the vertical distance ratio between the top of the cavity from the base of footing (H/B), the horizontal distance of void centerline to the footing center (X/B), on the behavior of footing are studied in this research. The results indicate that there is a critical zone under the footing in which the existence of void has no influence on the bearing capacity and stability of the footing. In addition, the use of geogrid reinforcement reduces the settlement and enhances bearing capacity. Finally, the bearing capacity factor and failure mechanism increase with increasing horizontal and vertical void distances ratios (X/B and H/B) and reinforcement layers.**

***Keywords-cavity; slope; strip footing; geogrid-reinforced; sand, finite element analysis***

## I. INTRODUCTION

In civil engineering, sometimes buildings and other engineering structures may sit on underground voids. Underground cavities that traverse the subsoil can be classified into two types: the ones of artificial origin due to human activity (e.g. installation tunneling, exploitation of underground quarries and mines, gas and water networks creation, etc.) or natural cavities formed by the action of water, which dissolves limestone or gypsum found in subsoil. Generally, the existence of underground voids on a foundation can cause large-scale disorders in the constructions, inducing the collapse of structures and the settlement of foundations.

There is a vast literature analysis of the carrying capacity and failure mechanisms of foundations resting on unreinforced soil with void through three principal methods: experimental investigations, numerical studies, and theoretical studies [1-5]. The numerical observation of [6] reported that the failure zone has developed considerably toward the void closest to the foundation and does not usually extend other voids. Theoretical methods [7] and centrifuge tests [8] have been performed to examine the stability of the void. Authors in [9] used a Finite Element Method (FEM) to investigate the bearing capacity and the failure mechanism of a strip footing built on double-voids. Their results indicate that the mode of failure depends on the size and location of the voids. Authors in [10] applied the procedure DLO to analyze the stability of footing situated on cohesive-frictional soil with single and dual square voids. The results implied that the presence of voids has a greater impact on c– φ soil compared to that on non-drained soil. The failure mechanism is related to several soil properties, the placement of voids, and the linear distance between two voids. Authors in [11] carried out a series of laboratory loading tests and numerical modeling simulations to investigate the impact of an underground void on the load-settlement behavior of a strip footing. They demonstrated that the FEM results are in good agreement with the experimental load-settlement curve. Also, the presence of subterrane voids can lead to stress concentrations within the soil, which can cause failure. Authors in [12] adopted FEM to study the collapse of strip foundations

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on the sand with single and twin continuous voids. The obtained results are in accordance with the theoretical and numerical solutions available.

For over 40 years, due to its relatively ease of use, and small cost, geogrid reinforced soil has been used in a variety of fields of geotechnical engineering [13, 14]. When a foundation is found above the void, one of the possible remedial measures to improve the bearing capacity and reduce the settlement and the performance of footing would be to reinforce the foundation soil with layers of geogrid. With this in mind, some researchers have also studied the behavior of a foundation built on reinforced soil containing the void [15-21]. Authors in [22, 23] presented an analytical solution for designing a planar geosynthetic reinforced soil system on a cavity. Authors in [24] conducted full-scale model tests on a shallow circular footing placed on geocell-reinforced sand bed overlying a clay bed having a circular void. They found that a substantial improvement of the bearing capacity of the footing can be achieved by providing an adequately sized geocell mattress, over the clay subgrade with the void. They also observed that, in order to have a great impact, the geocell mattress must extend beyond the void at a distance greater than the diameter of the void. Authors in [25] developed a laboratory-scale model with the intention of studying the effects of varied parameters on the performance of the strip footing supported by geogrid-reinforced sand over a void. The investigated parameters included void embedment depths, the number of reinforcement layers, and relative densities. They reported that loading pressure and footing settlement improved significantly with increasing void anchorage depth, number of geogrid layers, and relative soil density. Authors in [26] used numerical analysis to investigate the behavior of single and two adjacent strip footings placed on unreinforced/reinforced granular bed overlying clay containing voids. Their results show that the proving geogrid reinforcement increases the load carrying capacity of the footing in both cases. The influence of a single void on the bearing capacity is negligible when the void is situated at a critical depth greater than 5B and at a horizontal distance greater than 3B from the center of the footing.

The majority of the above mentioned studies focused on foundations resting on a horizontal ground, however, many of these structures are placed above or near slopes. There are some investigations that have been conducted to calculate the ultimate load carrying capacity of strip footings subjected to central loading near reinforced slopes without voids [27-31]. In contrast, strip footings adjacent to reinforced slopes with voids have received little experimental and theoretical/numerical research. Therefore, in the present paper, a series of finite element studies were conducted to analyze the bearing capacity behavior of footing on a reinforced sand slope with a single circular void subject to static vertical loading. Additionally, the benefits of geogrid-reinforcement application to stabilize strip footing and failure mechanisms of the sand slope were examined under different conditions of the void. To achieve this objective, a total of 80 numerical model tests were conducted with different depth ratios (H/B), horizontal spacing ratios (X/B) and reinforcement layers (N).

## II. FINITE ELEMENT MODELING

The finite element software PLAXIS was used to simulate the footing-void system in both condition unreinforced and geogrid reinforced sand slope. The sand surrounding the void is supposed to follow perfect and elastoplastic behavior law, where the rupture criterion is considered as Mohr–Coulomb in conjunction with non-associated flow rule, i.e. $\psi \neq \varphi$. The Mohr-Coulomb model was chosen for its simplicity and the availability of the necessary parameters. The adopted parameters of the analysis are summarized in Table I. The foundation was treated as an elastic beam element based on Mindlin's beam theory with significant flexural rigidity (EI) equal to 32,000MPa, Poisson's ratio of 0.2, and normal stiffness (EA) equal to 25KN/m$^3$. The void was considered to be circular in form and of diameter equal to the width of the footing. In addition, the void is simulated as a tunnel without a lining.

TABLE I. SOIL PARAMETERS

| Parameters | Name | Unit | sand |
|---|---|---|---|
| Model type | Model | - | Mohr-Coulomb |
| Dry density | $\gamma_{unsat}$ | KN/m$^3$ | 16.7 |
| Wet density | $\gamma_{sat}$ | KN/m$^3$ | 19.3 |
| Young's modulus | Eref | KPa | 1.2 104 |
| Poisson's ratio | $\nu$ | KPa | 0.30 |
| Cohesion | c | KN/m$^3$ | 1 |
| Angle of friction | $\varphi$ | (°) | 38 |
| Angle of dilation | $\psi$ | (°) | 6 |

Reinforcement geogrid, which is usually used to increase load bearing capacity, has only one tensile stiffness (EA=30KN). The reinforcement layers were simulated using the elastic geogrid element of Plaxis. The interaction between the soil and the geogrid is modeled on both sides through interface elements. The boundary conditions for all the models were chosen such that the vertical boundary is constrained horizontally and free vertically, while the bottom of the numerical model is fully fixed. During the generation of the mesh, 15 triangular plane strain elements were selected to model the soil, while the geogrid was modeled with 5 node elastic elements. The refined mesh option was adopted to guarantee a better representation of the stress field under the base of the foundation, near the crest of the slope, geogrid layers, and the void. The model slope geometry, generated mesh, and boundary conditions are shown in Figure 1.

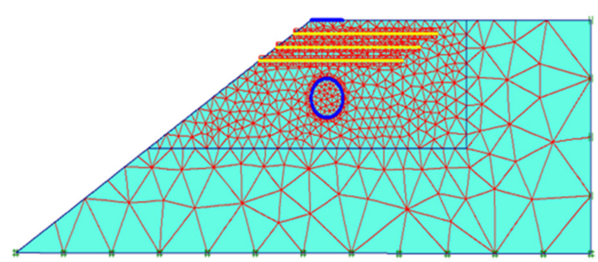

Fig. 1. The numerical model.

The calculation is performed in three phases: The first relates to the formation of the initial stress condition, the second stage deals with building the sand layers by placing the reinforcement elements and creating the void, and the last one is to load the strip footing. It is worth noting that for each analysis, a prescribed footing load was applied in increments, followed by iterative analysis, until failure. In all numerical models, the failure load is determined by the pronounced peaks in the load-displacement curves.

## III. VALIDATION OF THE FINITE ELEMENT MODEL

In order to confirm the numerical model, the slope surface was replaced by a horizontal ground surface. The bearing capacity factor Nγ values obtained by the finite element approach were compared with those given in the literature. Table II presents the numerical results for Nγ values associated with various friction angles (φ) obtained by different researchers. It is clear that the magnitude of Nγ increases with increasing φ. As shown in Table II, the computed values of Nγ are significantly lower than the solutions reported in [32], however, they are in good agreement with those reported in [33, 34], with a difference less than 6%. This good agreement can be considered as a validation of the numerical model obtained from this study.

TABLE II. BEARING CAPACITY FACTOR Nγ

| φ° | Current study | [32] | [33] | [34] | [35] | [36] |
|---|---|---|---|---|---|---|
| **25** | 7.24 | 9.7 | 6.76 | 6.76 | 10.88 | 6.74 |
| **30** | 15.47 | 19.7 | 15.07 | 15.67 | 22.4 | 15.24 |
| **35** | 31.03 | 37.5 | 33.92 | 37.15 | 48.03 | 35.65 |

## IV. TEST PROGRAM

Four series of tests were conducted to analyze the inclusion effect of the geogrid layers on the bearing capacity of shallow foundations supported by sand containing a void near a slope. Figure 2 illustrates the different tests conducted in this study with parameter details. In previous studies, several values of μ/B, h/B and L/B were proposed for foundations on geogrid-reinforced sand, where "μ" is the distance between the footing bottom and the first geogrid layer (L) the length of the geogrid, (h) is the distance between two geogrid layers, and B is the footing width.

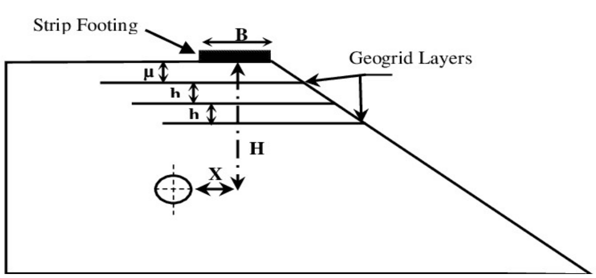


Fig. 2. Geometry parameters.

In order to study the best arrangement of geogrid layer inclusions, authors in [37, 38] reported that there are critical values for μ/B, and h/B ranging from 0.3-0.35, beyond which the reinforcement has no effect on the bearing capacity. On the other hand, the optimal value of L/B was 0.35, as determined in [25]. Based on these results, the values of μ/B=0.35, h/B=0.35, and L/B=4 were adopted in the current study in order to achieve maximum bearing capacity and reduce the settlement of the footing. Each series of tests analyzed the effect of one parameter while the other parameters were held constant. The variable parameters included the number of reinforcement layers (N), the depth between the foundation base and the crest of the cavity (H/D), and the horizontal distance of the void from the foundation centerline (X/B). Table III presents the different numerical programs and their fixed and variable parameters.

TABLE III. NUMERICAL PROGRAMS AND PARAMETERS

| Test series | Type of reinforcement | Variable parameters | | | Fixed parameters |
|---|---|---|---|---|---|
| | | N | X/B | H/B | |
| 1 | Unreinforced (without void) | 0 | - | - | μ/B=0.35<br>h/B=0.35<br>L/B=4<br>Tg (β)=2/3 |
| 2 | Unreinforced (with void) | 0 | 0<br>1<br>2<br>3 | 0.5<br>1<br>1.5<br>2<br>2.5<br>3<br>3.5 | |
| 2 | Reinforced (without void) | 1 - 2 - 3 | - | - | |
| 4 | Reinforced (with void) | 1 - 2 - 3 | 0<br>1<br>2<br>3 | 1.5<br>2<br>2.5<br>3 | |

## V. RESULTS AND DISCUSSION

A total of 80 model tests in 4 series were conducted on a strip footing constructed on a reinforced sand slope with a void to account for the influence of all the variable parameters. Two dimensionless factors are introduced to quantify the influence of the void and reinforcing layers on the bearing capacity in order to establish accurate comparisons between the numerical tests, knowing that authors in [4, 6, 26] also assessed the impact of void and reinforcement soil in terms of reduction factors, not in terms of ultimate bearing capacity. The first parameter is the bearing capacity ratio (ih), which can be given in the form shown in (1). This factor is defined as the ratio of load-bearing capacity of the footing on the unreinforced sand with a void and without void respectively.

$$ih = \frac{q_{uv(\text{with a void})}}{q_{u(\text{with out void})}} \quad (1)$$

The second parameter is used to assess the combined effect of reinforcement layers and the existence of the void on bearing capacity. This parameter is defined as ihr, i.e. the ratio between the load-bearing capacity of the strip footing on the reinforced soil with a void to that of unreinforced soil without one:

$$ihr = \frac{q_{uvr(\text{with a void})}}{q_{u(\text{without void})}} \quad (2)$$

### A. *Effect of Geogrid Layer*

To examine the effect of geogrid-reinforcement, the strip footing was placed on the reinforced sand slope with 3 layers of reinforcement (N = 1, 2, and 3). Figure 3 represents the variation of the reduction factor ihr with different void embedment depths ratios (H/D = 1.5, 2, 2.5, and 3), when the void is assumed to be located directly below the centerline of the foundation (X/B = 0). It can be observed that the bearing capacity increases due to the provision of the reinforcement layers. In addition, the bearing capacity of the foundation was increased along with the number of layers of geogrid reinforcement. Additionally, as the mass of the sand layer above the void increases (increasing H/D), the shear resistance increases.

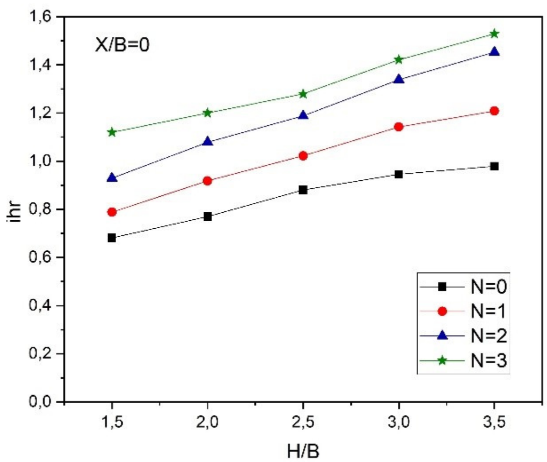


Fig. 3. Variation of reduction factor ihr at different H/B.

Therefore, significant stability of the void had been observed. Also, the ihr increases, regardless of the number of geogrid-reinforcement layers. Figure 3 displays that in the case of reinforced sand when N = 1 and H/D attained a value of 3, the bearing capacity values of the strip footing tended toward the bearing capacity of the strip footing on unreinforced sand without a void. However, with up to two layers of reinforcement, the bearing capacity of strip footing on reinforced sand with a void, is greater than the unreinforced sand's without a void. These results demonstrate the effectiveness of the reinforcement layers in improving the ultimate bearing capacity of strip footings resting on a sand slope with a void.

### *B. Effect of Void Depth*

The embedment depth of the void from the soil surface is one of the main parameters of soils with a void. Figure 4 reveals the variation of reduction factor ih versus depth ratios (H/B) varying from 0.50 to 3.50 with an increment of 0.5. Interestingly, it is observed that the value of ih increases continuously with increase in the value of depth ratios H/B up to a reach a limit value at H/B = 3.5, beyond which the reduction factor becomes constant. This limit value is called the critical depth, Hcr. At this specified depth. the footing behavior converges to that without void. A similar result was reported in [25]. A significant reduction in the bearing capacity value was observed when the void was located at H/B = 0.5 and 1. This happened because the soil layer above the void was thin and the failure surface gets smaller than the one without a void. Therefore, low pressure is necessary for the failure surface to achieve the slope, causing a decrease in bearing capacity.

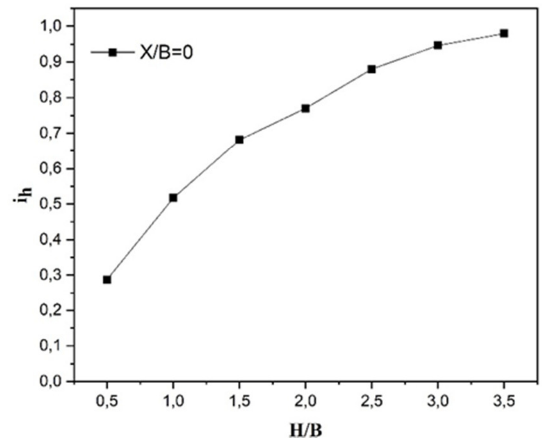


Fig. 4. Variation of reduction factor ih versus different depth ratios for X/B=0.

### *C. Effect of Horizontal Distance*

Figure 5 reveals the variation of reduction factors ih and ihr, versus depth ratios (H/B), for different horizontal distance ratios (X/B= 0, 1, 2, and 3) and reinforcement layers N=0, 1, 2, 3.

(A)

(B)

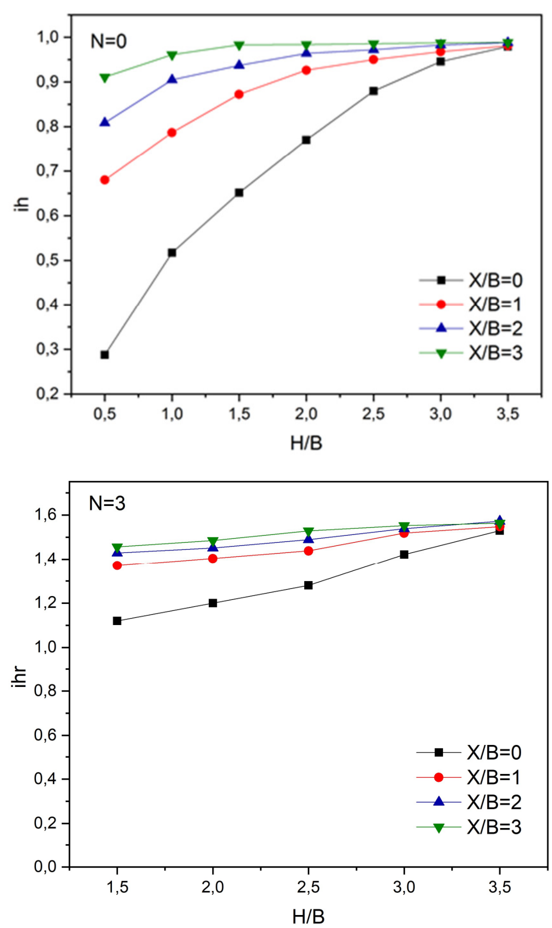


Fig. 5. Variation of ih and ihr versus different depth ratios H/B for varying X/B.

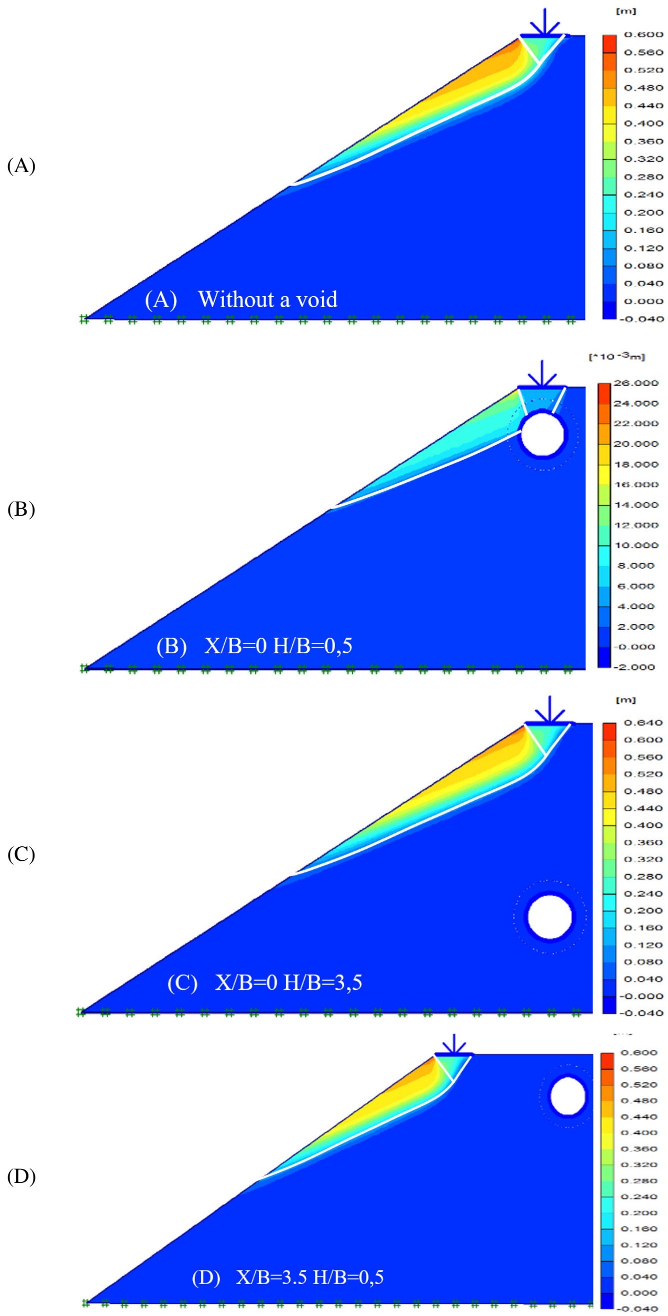


Fig. 6. Failure surface for unreinforced sand slope.

As shown in Figure 5(A), the reduction factor is affected by the position of the void (X and H). Furthermore, the value of bearing capacity increases with increasing depth distance ratios (H/B, X/B) and number of reinforcement layers. It is observed from Figure 5 that the maximum reduction on the ihr is noted when X/B = 0 and H/B < 3. For unreinforced sand, if the depth ratio H/B or X/B is greater than 3.5 and 3.0 times the width of the footing respectively, the bearing capacity of the footing does not affect by the presence of the void, while ih is greater than 0.8. For the case of reinforced sand as shown in Figure 5(B) when N=3 for different X/B ratios, ihr remains constant and the corresponding value approaches 1.0. In this case, the bearing capacity of the footing is similar to the case without void, while the influence of void becomes insignificant. As reported in [39, 40], this behavior occurs because the maximum extend of the failure zone in cohesionless soil is 3B below the footing and 2.5B on both sides. Therefore, the void is located out of the soil shear zone.

## VI. FAILURE MECHANISM

Figure 6 shows the failure surfaces for the strip footing close to the unreinforced sand slope with or without a void. Various horizontal spacings between void and footing X/B = 0, 1.0, 2.0, and 3.0 and different embedment depths of void H/B were considered. As shown in Figure 6, the failure mechanism depends significantly on the location of the void. When the foundation is situated on an unreinforced sand slope without void, a triangular zone formed under the foundation. The failure surface occurs at the footing side and extends laterally towards the slope, as illustrated in Figure 6(A). For the unreinforced sand case with a void, and with depth ratios X/B = 0 and H/B < 3, as can be seen in Figure 6(B), the failure surface doesn't form the triangular wedge and the void is located in the shear zone of the failure mechanism. However, the slip surface extends vertically connecting both the edges of the foundation to the upside of the void crest and is appearing smaller than the one in the case without void. On the other hand, if X/B or H/B are above 3 and 3.5 respectively, the void is located out of the rupture zone. In addition, the behavior and failure mechanism are similar to the strip footing on unreinforced sand without a void (see Figure 6(C)-(D)). This proves that the void does not affect the load-bearing capacity of strip foundations.

## VII. CONCLUSION

The current numerical study analyzed the effect of underground void on the bearing capacity behavior of strip footing sitting on the crest of unreinforced and geogrid-reinforced sand slope. The main conclusions of the study are:

- It was found that the ultimate bearing capacity depends on the location of the underground void (X/B and H/B) and the number of reinforcement layers.
- The presence of voids always reduces the load carrying capacity of the footing in both unreinforced and reinforced cases.
- The ultimate bearing capacity increases with distance (X and H).
- Using geogrid reinforcement increases bearing capacity and reduces the settlement of the strip footing.
- The load-bearing capacity of a strip footing increases with increasing number of reinforcing layers.
- There is a critical distance (Xcr = 3 and Hcr = 3.5) beyond which the influence of the underground void on the footing stability is considered to be negligible.
- The depth and width of the failure surface increase with increasing vertical and horizontal distance (X and H).

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