



## A Review Study on Foundation above the Soil Containing Voids: Challenges and Obstacles

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### ABSTRACT

Foundations constructed on sandy soils that contain underground voids or cavities often face significant geotechnical challenges. Underground cavities occur as the results of natural causes, manmade causes or sometimes a complex combination of both. Despite considerable research on foundation performance in soluble soils, the effects of cavity geometry specifically, cavity depth and horizontal position relative to foundation centers and load eccentricity on the bearing capacity This paper discusses an extensive survey on the previous investigations the challenges and obstacles on the conducted foundations conducted on soil containing voids footing not fully understood. Various factors were considered effect of void size, depth, void location relative to the foundation. These studies have effectively shown that the presence of voids directly affects soil behavior, leading to reduce shear strength, decrease bearing capacity, and increase settlement, which can cause sudden failures. The greatest impact occurred when the voids were located within the critical zone below the foundation, while their effect decreased with increasing depth or horizontal distance.


## 1. Introduction

Foundations constructed on sandy soils that contain underground voids or cavities often face significant geotechnical challenges. Underground cavities occur as the results of natural causes, manmade causes or sometimes a complex combination of both. The natural occurrence of the cavities is due to mainly the geological settings of underlying rocks, especially soluble rocks such as limestone, dolomite chalk, gypsum. In this type of the geomaterials, the creation of the cavity, is a complex combination of chemical erosion, that goes on through a certain period of times

(usually geological times), and mechanical erosion. The researchers developed a range of methods to improve the performance of geotechnical structures and soil characteristics. Applying these methods can be difficult due to their high cost and the constraints imposed by site conditions. Experimental observations revealed three distinct failure mechanisms for a single void beneath a strip footing, contingent upon the void's size and position. Failure of the void's roofing Simultaneous failure of the roof and wall. Bearing failure in the absence of void failure [1] Upper bound calutaions were provided to explain the difference in bearing capacity realised. Geotechnical parameters

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affecting the undrained bearing capacity having voids and also soil failure mechanism is related to some of the soil properties, location of single void, as well as linear distance between two voids, which are all presented by recently conducted investigation. The local shear failure mechanism is the most ancient process identified in the soil surrounding the hole. The friction angle enhances stability, whereas the horizontal distance and descriptor diameter diminish it. A parametric analysis was conducted to examine the instability (collapse), displacements, and deformation field of the ground surrounding the cavity, both with and without a foundation, focusing on the effects of the distance  $D$  between the foundation and the cavity, as well as the height  $H$  and width  $L$  of the cavity[2].

The effect of the distance between the cavity and the Earth's surface demonstrates that displacement increases as the cavity nears the surface; at reduced distances, the displacement becomes more significant. The deformation field will be substantial and indicates the collapse of the underground cavity. The influence of width  $L$  The displacement is almost directly proportional to the widening of the subsurface hole; notable impacts on ground deformation fields are evident regardless of the presence of foundations, attributable to the cavity's breadth. Furthermore, the failure of the subterranean void transpires with an expansion in its breadth[3]. The influence of height  $H$  on the fluctuation of elevation, whether with or without foundations, leads to divergent collapse (destabilisation) regimes of underground cavities and progressively expanding deformation fields, particularly displacements associated with height [4].

## 2.cavities

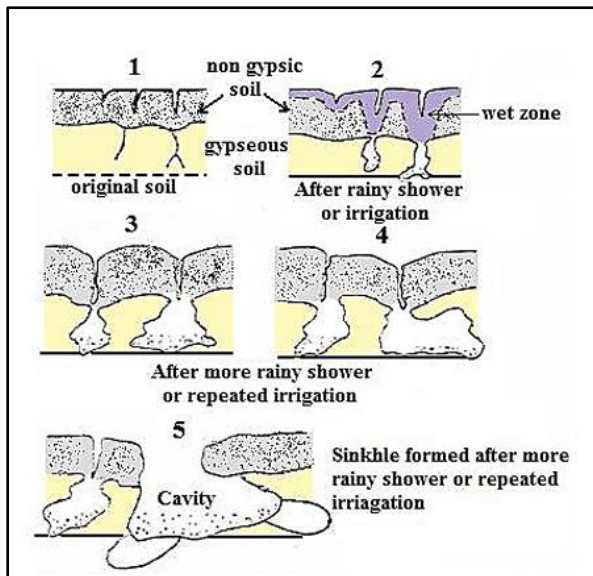
In geotechnical engineering, voids denote the unoccupied gaps existing between soil particles. These spaces may contain air, water, or a combination thereof, and they significantly influence the mechanical properties of soil, particularly in sandy soils .Voids may also manifest as bigger discontinuities or voids within the soil mass, resulting from natural

processes (such as erosion or dissolution) or anthropogenic operations (such as excavation or inadequate compaction). Voids frequently develop beneath structures, necessitating careful consideration, as they can lead to structural damage and fatalities. Voids can occur due to mining, tunnelling, or the dissolution of cavities in soluble rock. Solution cavities can form at varying depths within the soluble bedrock; there are also examples where the soluble bedrock undercut due to erosion at the interface with soil resulted in an overburden soil that bridges unsupported void. Numerous caves have been created by mining activity beneath the surface. Increasing urbanisation as a consequence of increasing population is forcing sprawl into areas previously avoiding mining activity, and this has prompted more extreme concern from geotechnical engineers that urban building foundations may be rendered unstable. Increase in Urbanization and Tunnel Locations Concerns Concerning Foundation Durability over Soft Ground Tunnels In discussing the construction of foundations over a void, the geotechnical engineer typically considers four alternatives: (1) filling, (2) spanning by either pile or caissons down load-bearing into underlying soil/bedrock to carry loads over the void - otherwise fill it; (3) excavation through the foundation under grade at both ends of a void: and (4) replacing where and how one builds their foundation away from and/or back to that area. You can only move if you have enough space. Options other than tunnels however are costly or impractical such as for tunnelral loading conditions as shown in figure (1) [5].

### 2.1 Soil Containing cavity's

The cavities that form inside the soil are a real problem that is difficult to expect. The presence of cavities inside the soil directly affects the capacity of the structures. The presence of cavities in the soil results in serious issues that shorten the structure's service life and produce losses that could be monetary [6]. Considering the location and shape of the cavity is a challenge for engineers due to the difficulty of

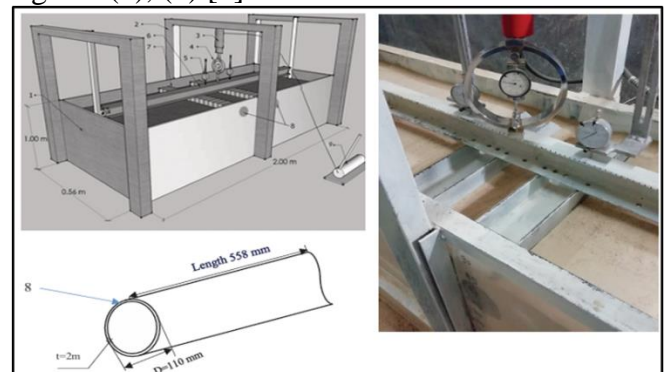
determining their location, shapes, and location [6], [7]. There are several reasons according to which cavities are classified depending on the reasons of deform from the main reasons may be natural and artificial [8]. The natural causes for the formation of cavity is the presence of the elements involved in the soil composition which are affected by the weather and external factors that affect the soil. The presence of soluble salts such as gypsum, dolomite and limestone are one of the most important natural causes. As well as the climate change that the earth is going through, such as the melting of ice confined inside the soil and drought processes. One of the main causes of the cavity in the soil is the industrial reasons, which human interferes with in their formation, and among the reasons are the old underground buildings such as graves, tunnels, old walls and all the facilities that



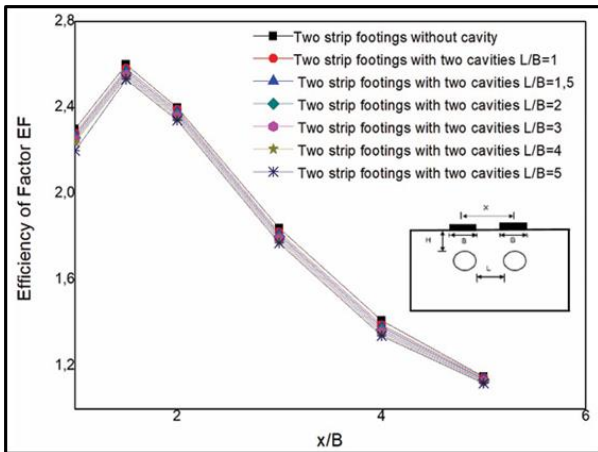
**Figure(1)** Formation of sinkholes in extremely gypsiferous soils

human builds inside the soil. The shape and the volume of this cavity is different from soil to other depending on them reasons of deform. The treatment of all cavities or the necessity for deep foundations would substantially elevate construction expenses. Consequently, it is imperative to ascertain the bearing capability of strip footings under these conditions during the preliminary design phase, while prioritizing engineering safety and cost efficiency. Circular

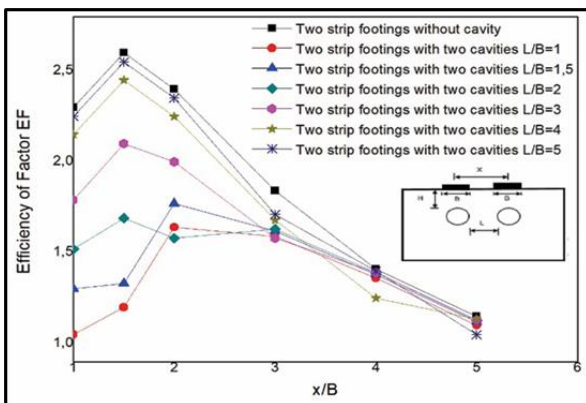
voids and a circular footing sitting on kaolinite soil were used for the model footing tests, and the outcomes were compared with those produced by three-dimensional finite element modeling. Footings with and without voids were analyzed to compare the results of bearing capacity and settlement under various conditions. This study also takes into account the appropriate footing depth and comes to the conclusion that if a void is found in the critical zone directly below the base of footings, it could significantly affect stability. Experimental models were developed to evaluate the effect of voids on the load-bearing capacity of two adjacent footings on granular soil, as shown in figure (2). Their results showed that when the distance between the footings and voids is greater than three times the footing width, the cavity impact becomes insignificant. They also came to the conclusion that there is a critical horizontal distance at which the footing's bearing capacity decreases and a substantial hollow depth, as seen in figures (3), (4). [9].



**Figure (2):** Test setup schematic diagram 1) a steel test box 2) steel load frame; 3) hydraulic jack; 4) proving ring; 5) dial gauge; 6) steel beam; 7) steel footing model; 8) PVC 110 mm cavities; 9) A roller compactor[9].



**Figure (3)** shows how EF varies with  $x/B$  in the following scenarios:  $L/B = 1.0$ ,  $L/B = 1.5$ ,  $L/B = 2.0$ ,  $L/B = 3.0$ ,  $L/B = 4.0$ , and  $L/B = 5.0$ ; two strip footings with and without cavities ( $H/B = 3$ ) [9].



**Figure (4)** Variation of EF as a function of  $x/B$  in the following cases: two strip footings without cavity and with cavity ( $H/B = 1$ ); ( $L/B = 1.0$ ,  $L/B = 1.5$ ,  $L/B = 2.0$ ,  $L/B = 3.0$ ,  $L/B = 4.0$ , and  $L/B = 5.0$ ) [9].

Experimental Study on the Influence of Interference to Load Capacity Related with 2 Proximate Foundations in Granular Soil It was evaluated that the cavities and dual footing interference had an effect on bearing. Results reveal that cavities and dual footing interference at five different separation distances influenced bearing capacity and efficiency factor, while the effect of size on shear strength was almost stabilized as separated distance increased. Underlying voids negatively contribute to the final analysis of bearing capacity for shallow foundations. Subterranean processes such as solubilization of soluble materials, leakage from deep CO<sub>2</sub> storage tanks and melting ice lenses in the subsurface might lead to void formation [10]. Kiyosumi et al. [11] It implies that there are two

aspects to this problem. Regarding the stability of voids and the footings' ability to support loads on void-containing soils Extensive experimental studies have revealed three potential failure pathways for a single void: (1) bearing failure without accompanying analyses were analysed namely, (2) ultimate surficial loading conditions accompanied by emptying maintenance execution approaches. Centrifugal examinations [12] Theoretical solutions [13] were conducted to examine the stability of the void. Despite the introduction of various methodologies (Investigating the bearing capacity of footings on soils with voids is still crucial because of financial and spatial constraints, such as using reinforcement that penetrates a rigid stratum beneath a void, excavating and placing foundations beneath voids, and moving a construction project [14]. Baus and Wang [14] performed limited experiments on strip footings placed on compacted silty clay. A compacted clay was used for later analyses [15]. In a series of studies on a gypsum-sandy soil mixture containing voids, Al-Tabbaa et al. [16] demonstrated the impact of cavity size, offset, and depth on the system's stiffness and strength Lee et al [17] evaluated the undrained bearing capacity of a vertically loaded strip footing with single and dual voids using the Finite Element Method, looking at how soil stiffness affected the bearing capacity factor of strip footings above single square voids. Regardless of the location of the void, the stiffness of the soil has no effect on the capacity factor. Soil stiffness has little effect on a surface footing's bearing capacity on the ground. Design charts were created using a collection of dimensionless parameters. Additionally, they looked into how load inclination affected the undrained carrying capacity of footings on voids [10].

## 2.2 Causes and formation zones of voids or cavities

Void formation may transpire directly beneath the foundation or within any segment of the crucial area, particularly the zone delineated by the pressure bulb, thus impacting the stability of the footing. Various geotechnical and

geological investigations delineate the causes and locations of cavities or voids like this:

1. Excavation in the form of blasting is in fact dynamic loads imposed onto the surrounding soil thereby creating voids below ground level.
2. In urban areas, storm or sewer pipes, natural reservoirs, conduits, channels, and subterranean water tanks are used as specific scenarios to meet the needs of an enforced civilization.
3. The chemical reactions with water and/or other reagents are used to combine the ingredients (salts, dolomite, gypsum, limestone) used as cement. The area created by the movement of this liquid — which punched round holes into the earth at a higher frequency. The lithological properties of rocks & soils can lead to the development of cavities.
4. The predominant voids are found in calcareous silt due to its significant vulnerability to compaction and disintegration, linked to the underground water flow direction.
5. Subterranean infrastructure, including tunnels, marine subways, tanks, and pipes, can deteriorate due to differential settling of buildings, municipal solid waste, improperly compacted backfill, and stress cracks in unsaturated cohesive soils.
6. Void formation occurs due to a bearing stratum that is either softer or stiffer than the against layer which forms strata in stratified soil deposits. Most of the reported cavities exhibited different dimension categories, which are presented in Figure. (5)[18]; from 10 to 300 cm.

Kuwano et al. [19] have disclosed that the majority of documented cave-ins historically occur during the rainy season, and even minor cavities in sandy soil can spread significantly more rapidly when the earth is saturated. Nevertheless, limited study has been performed on cavity expansion and loosening, with the majority being qualitative (Sato et al.)

[20]. The answers to numerous inquiries, including the variability of expansion rates with soil and time, the reduction in strength in loosened areas, and the identification of small cavities that may lead to sinkholes, remain undiscovered.



**Figure(5)** Images of cavities exhibiting various dimensions and locations [18]

### 3. The challenges and obstacles containing voids underneath the footing

Numerous experimental and analytical techniques have been used to study the stability of foundations over subsurface voids. According to Aziz, L. J. [21], When a cavity is present in sandy soil, the strip footing settles more quickly and the effective shear strength is decreased, increasing the chance of an abrupt and quick failure (punching the strip footing into the sandy soil containing the cavity). In many studies, a significant aspect of foundation design, which affects the carrying capacity of foundations, has been studied, and this aspect of foundation design was one of the most important ones. Various methods including analytical study, experimental test and computational analysis have been applied to understand the behavior of footings with voids. Shallow foundations have a reduced ultimate load capacity if there are voids present beneath them.

A model tests was conducted on circular footings placed above voids in clay soil, comparing the results with three-dimensional finite element simulations. It was found that footing stability is significantly compromised

when the void exists inside the critical zone beneath the foundation [15]. In a different investigation, the yielding pressure of strip footings across different voids was determined using a two-dimensional plane strain finite element model, emphasising the nearest void that significantly influences footing behaviour compared to other voids [13]. When sand cushioning is placed on top of voids of clay, it was shown that it collapses like punched shear failures occur in soils. Soil arching was found to cause these effects, so the results were improved due to this soil-arching effect at increasing foundation depths. Bearing pressure and footing settlement are influenced by the depth of the geocell layer, the base geogrid layer, the width of the geocell layer, and the relative density of the sand fill. They all expanded, mostly in terms of bearing capability, which greatly increased the number.

### **3.1 Effect of void size**

These voids' size affects the structural capacity and causes serious structural damage. An investigation of the behavior of a scale model anchor plate installed in sandy soil in a lab setting under the influence of three cavity diameters: 10 cm, 15 cm, and 20 cm. The results indicate a direct impact on the capacity of the plate anchor and the nature of failure that occurs inside the soil to counteract uplift stresses[22] . The findings show how cavity volume affects anchor capacity, showing that different cavity sizes at the same location reduce anchor capacity by a percentage that depends on the cavity volume Makki et al[23]. evaluated how well a concrete slab under eccentric loading performed on earth with voids of different sizes, locations, and shapes. According to the investigation, soil with a circular hollow has a better stress distribution than soil with different geometries. When the anchor plate is subjected to an upward load in sandy soil, cavities of varying sizes, shapes, and locations may emerge, leading to considerable vertical displacements of the anchor plate and different failure mechanisms within the soil [24].

This study examines the stability of surface footings having circular voids beneath the footing's center that are supported by varying sand thicknesses on top of clay layers, both eccentrically and centrally loaded. The load-bearing capacity ratio significantly decreases as the void's diameter grows. When  $d/B = 3$ , the ratio remains consistent over all diameters of the underground vacuum, despite potential variations in different scenarios. This exception can be elucidated by the observation that at this depth, the behaviour resembles that of the scenario devoid of the void[25].

The stability of surface footings, both centrally and eccentrically loaded, with a continuous circular void beneath the footing's center and a strong sand layer of varied thickness  $H$  on top of weak clay, was investigated numerically. Lastly, the finite element program Plaxis was used to determine the strip footing's bearing capacity both with and without a geogrid placed over it.

The study's findings show that the void depth ratio affects the final bearing capacity; more precisely, a higher void depth ratio is associated with a lower bearing capacity ratio. With the exception of footings with a void depth ratio of three, the ratio of a footing's bearing capacity dramatically drops as the cavity diameter grows. The ratio of bearing capacities is unaffected, and the footing's behavior at such an embedding distance is similar to that of the footing without a void[25].

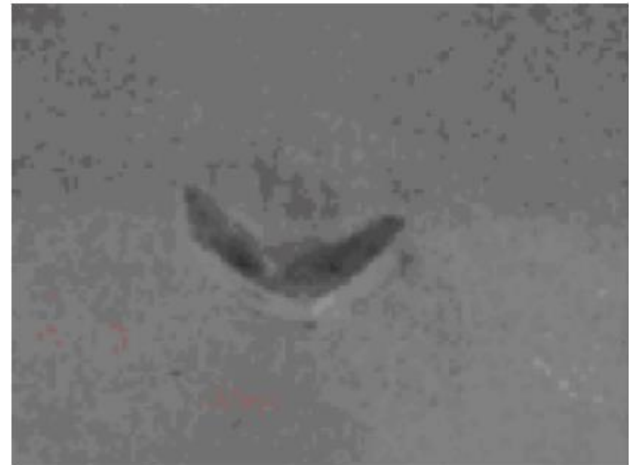
Analysis was done on the failure mechanism of strip footings located above granular soils. According to the study's findings, there is a critical depth below which cavities have no effect on foundation function. When cavities are located above this critical depth, the position, size, and depth of the footing all have an impact on the foundation's capacity to support loads. Additionally, the angle of load inclination. While maintaining a constant depth from the cavity crown to the footing base, increasing the cavity width significantly reduces the foundation's load-bearing capacity[26].

### 3.2 Effect of void depth

Abdelghani & Azeddine [27] The footing's bearing capacity and settlement characteristics are greatly impacted by the cavity depth  $D$ , which is situated below the slope crest. Because the carrying capacity of the footing is directly connected to the depth of the cavity, the likelihood of collapse rises when the distance between the cavity and the base is small. The bearing capacity increases from 20% to 42% and from 42% to 91% as the depth increases from  $1.5b$  to  $2b$ ,  $2b$  to  $2.5b$ , and  $2.5b$  to  $3b$ . Zhao, L., et al. conducted an important study (2018) [28] found that the influence of depth  $H/D$  distribution on power dissipation is roughly symmetrical, with the exception that the extent of shear bands in adjacent surface fluctuations changes as  $H/D$  increases. The failure range extends from roughly  $1.5D$  to  $2D$  at  $H/D = 2$  and from  $2.3D$  to  $3D$  at  $H/D = 4$ , as the cavity depth increases.

A study conducted by Mansouri, T., et al. [29] aimed to ascertain the depth of the voids. It was determined that, regardless of the eccentricity of the load and the distance of the void from the centerline of the foundation, the footing's bearing capacity increases as the depth of the void's crown increases, peaking at a vertical distance between the void and footing  $(H/B) = 2$ . The effect of the vacuum on the bearing pressure seems to be similar to that of a footing without a void below this depth. There is a key area beneath the footing, and only when the void is situated inside that area does the footing's bearing capacity change significantly.

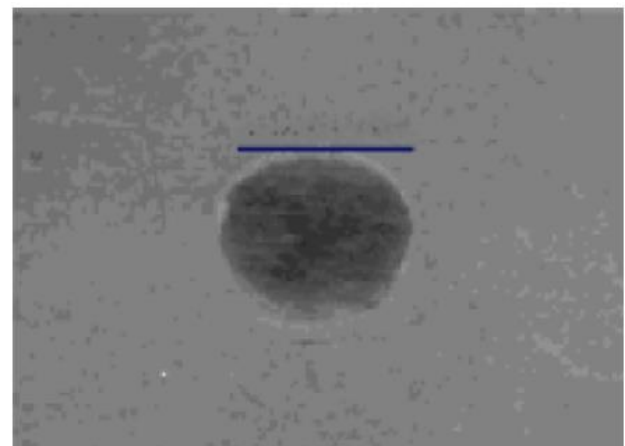
In contrast to the foundation bed, where voids are missing, the  $cr$  parameter of the void depth to the void diameter  $(H/D)$  in unreinforced sand with a relative density of 72% is roughly 3.5–4. This research demonstrates that when using the general shear mechanism, the no-void condition estimates of critical depth for an approximate upper bound of footing general shear failure are inaccurate [30]. As shown in figure (6)



(a)



(b)



(c)

**Figure (6)** Void deformation following unreinforced testing for varying void embedment depths,  $D_r$  72%, and  $H/D$  (a) 2, (b) 3, and (c) 4 [30].

When a single void is located at a critical depth greater than  $5B$  and at a horizontal distance greater than  $3B$  from the centroid of the

footing, it has a minor impact on bearing capacity [31].

According to the results, Zhang and Lin [32]. The vacuum prevents the load from being transmitted through the soil. The load is spread to both sides of the void as a result of the vertical distance  $H$  and the horizontal distance  $L = 0$ , which reduces the contact force chain of the soil beneath the void. The load is mostly concentrated on the left side of the void when  $L > 0$ , which causes the left side to have a much larger contact force chain than the right.

The Rajput[33] According to the study, the strip footing's bearing capacity gradually increased as the flexible void's depth increased. When the  $L/D$  ratio reaches or exceeds 4, a flexible void's impact on the footing decreases because the void extends beyond the load's area of influence.

[34] It is noted that augmenting the cavity depth in relation to its horizontal offset mitigates the direct effects of cavitation on stress distribution, hence diminishing load-induced stress concentrations and enhancing bearing capacity, particularly in soils with low dissolution levels.

A subsequent investigation demonstrated that the bearing capacity value escalates with increasing depth-to-breadth ratios ( $H/B$ ,  $X/B$ ) and the quantity of reinforcement layers. When  $X/B = 0$  and  $H/B < 3$ , the coefficient (the ratio of the load-bearing capacity of the strip footing on reinforced soil with a void to that of unreinforced soil) is reduced the most. The bearing capacity of a footing in unreinforced sand is unaffected by the presence of a void when the depth ratios  $H/B$  or  $X/B$  exceed 3.5 and 3.0 times the footing width, respectively, as long as  $i_h$  (the ratio of the load-bearing capacity of the footing on unreinforced sand with a void to that without a void) is greater than 0.8[35].

Data on the foundation created with circular voids (with two) and critical condition analysis of strip footings on cohesive-frictional soil have been published by Rouchi and Nozari [36] using the mixed lower bound-finite

element method. The footing carrying capacity was significantly lowered by the existence of voids, according to the results, however this reduction lessened as the void's depth and distance from the foundation rose. Moreover, soil strength properties are essential elements since increased cohesion results in greater bearing capacity especially at the mid-range. Comparative studies on the different charts show that soil with more friction has greater capacity, however it suffers a comparatively larger drop in bearing capacities due to the voids. The bearing capacity is significantly impacted negatively by the voids' closest proximity to one another. According to the foundational parameters (void-to-footing width ratio,  $B_d/B=0.5$ ; void diameter-to-footing width ratio,  $D/B=0.25$ ), which are identified as a crucial area directly beneath the foundation, the presence of the dimensionless cohesion parameter and the internal friction angle of the soil resulted in an overall improvement in the bearing capacity of the foundation. Furthermore, the capacity is significantly increased by deepening the twin voids.

The bearing capacity of strip footings on a sand base with voids was assessed numerically using the PLAXIS program. The assessments suggest that cavities could reduce the footing's carrying capacity. Footing performance is largely affected by the size (diameter ratio –  $D/B$ ) and placement ( $H/B$ ) of the void. As the embedment depth of the void ( $H/B$ ) increases, the bearing capacity actually approaches that of a footing on sand without any void. Consequently, the effect of void vanishes as the footing depth to width ratio ( $H/D$ ) or approaches approximately 3.5[37].

To assess footing performance under cyclic loads, researchers conducted laboratory tests on strip footings using both unreinforced and geogrid-reinforced sand with voids. Their results showed that settlement increases when a void is present in the failure zone but decreases when the void is deeper and there are more layers of reinforcement[38].

#### 4. Conclusion

Despite substantial research on foundation performance in soluble soils, the impact of cavity geometry—specifically cavity depth and horizontal alignment concerning foundation centers and load eccentricity—on bearing capacity is still little understood. The following summary may originate from the above listed studies: -

1. Void characteristics such as size, depth, and location are key factors affecting foundation performance
2. The presence of voids in sandy soils reduces shear strength and stiffness, leading to decreased bearing capacity and increased settlement.
3. here exists a critical depth below which the presence of the void has negligible influence on the footing performance.
4. horizontal location of voids affects the path of load transfer within the soil, with the effect decreasing as the void moves further from the foundation center.

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