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Impact of Groundwater Table Fluctuations on the Bearing Capacity of Shallow Foundations in Sandy Soils: A Parametric Analysis Using PLAXIS 3D Modeling

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Abstract
The critical influence of groundwater table (GWT) fluctuations on the bearing capacity of shallow foundations in sandy soils is examined in this study, a component sometimes undervalued in geotechnical design. Using sophisticated PLAXIS 3D numerical simulation, a thorough parametric analysis was done to evaluate how different GWT values affect the ultimate and allowed bearing capacities across a range of foundation sizes (1m x 1m to 4m x 4m) and embedment depths (0. 00m to 1. 50m). As the lower of the capacity based on a factor of safety ($q_u/3$) and the settlement-limited capacity (S_{25mm}), the allowable design bearing capacity (q_{all}) was calculated. The results show a notable inverse correlation between foundation size and GWT sensitivity: smaller foundations (1m x 1m) had the most major reductions in bearing capacity (up to 45. 97% for surface foundations at GWT=0. 00m), whereas larger foundations (4m x 4m) showed more stability (maximum 7. 48% reduction under comparable conditions). Increased embedment depth helped to reduce these negative consequences throughout all foundation sizes. One of the most important results is that keeping a minimum of 1. 00 m between the groundwater table and the foundation base virtually removes the effects of groundwater. The study also underlines non-linear correlations in bearing capacity reductions, therefore indicating complicated soil-structure interactions. Emphasizing the need for thorough groundwater studies for structural safety and best performance, this study offers vital data and ideas for improving predictive models and producing superior design guidelines for shallow foundations in sandy soils.
Keywords. Groundwater Table (GWT), Shallow Foundations, Bearing Capacity, Sandy Soils, Embedment Depth, PLAXIS 3D.

Introduction

Shallow foundations remain a cornerstone of civil infrastructure, efficiently transferring structural loads to the underlying soil. However, their performance is highly sensitive to environmental factors, particularly fluctuations in the groundwater table (GWT). Rising GWT levels can degrade soil strength, amplify settlement, and trigger catastrophic failures—a concern exacerbated by climate change and urban development. Globally, incidents such as the groundwater-induced subsidence in Libya [1-2], and rain-driven settlement magnification in Singapore [3] underscore the urgent need for robust predictive models to address these geotechnical challenges.

Previous studies have established critical links between GWT variations and foundation behavior. For example, [4] demonstrated that a rising water table causes a considerable rise in settlement, particularly in soft soils, where the correction factor (C_w) varied between 2.9 and 4.4 in dense soils and between 4.9 and 7.6 in soft soils. [5] In a study using laboratory models of foundations in various shapes (square, circular, and rectangular) in sands with different relative densities (38% and 77%), it was found that the effect of rising water extended as deep as six times the foundation's width (6B), with the settlement rate increasing as the water got closer to the foundation level. Furthermore, a previous study [6] has shown that a rising water table decreases bearing capacity significantly, particularly as it gets closer to the foundation level, where settling in saturated soil doubles as compared to dry conditions. Additionally, he noted that the impact of elastic and plastic parameters (like E, C, and φ) is more noticeable within particular ranges and that their efficacy diminishes when they surpass critical values (like $E > 60,000$ kPa or $\varphi < 33°$). Additionally, [7] documented a 30.8% reduction in bearing capacity for sandy soils under a 150 mm GWT rise, while [8] observed a 58% settlement increase in strip footings when the water table reached the foundation base. Historically, researchers have relied on empirical corrections (e.g., Terzaghi's formulations) or 2D numerical models (e.g., PLAXIS 2D, FLAC 2D) to evaluate these effects. However, while 2D simulations offer computational efficiency, they inherently oversimplify complex soil-structure interactions. For instance, such models fail to capture lateral stress redistribution, edge effects around square footings, and spatially variable pore pressure gradients—limitations that can lead to significant inaccuracies.

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To bridge this gap, this study employs advanced PLAXIS 3D finite element modeling, which explicitly resolves three-dimensional interactions, including asymmetric settlement patterns and localized shear zones. Unlike conventional approaches, this methodology enables a holistic assessment of stress redistribution and failure mechanisms under dynamic groundwater conditions. By conducting a systematic parametric analysis—spanning foundation sizes (1m×1m to 4m×4m) and embedment depths (0.00m to 1.50m)—the research quantifies the sensitivity of allowable bearing capacity (q_{all}) to GWT variations. The q_{all} is determined as the lesser of two criteria: the factor-of-safety-adjusted capacity ($q_u/3$) and the settlement-limited capacity (S_{25mm}). The primary objective of this work is to evaluate how GWT fluctuations influence ultimate and allowable bearing capacities in sandy soils, and to quantifies the mitigating effects of foundation size and embedment depth on groundwater-induced risks.

Methods

Using numerical modeling in PLAXIS 3D, this study investigates the bearing capacity of shallow foundations, especially concerning the impact of groundwater level fluctuations. Building on the validated finite element model and material characteristics from [9], the approach expands their framework to examine groundwater impacts. The model configuration, mesh creation, boundary conditions, material properties, and validation approach are discussed in the following chapters. Figure 1 shows a review of the chosen approach.

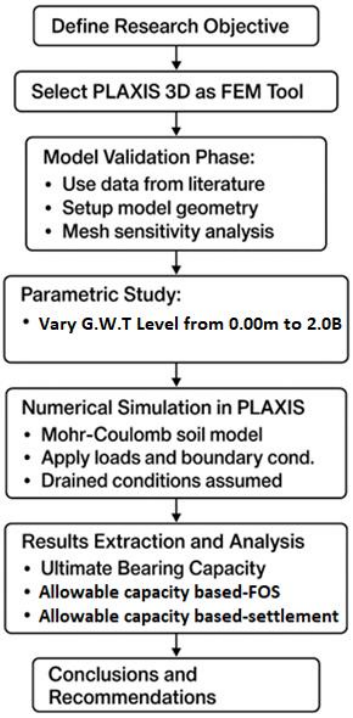

Figure 1. The chosen approach

PLAXIS 3D Model Setup

Employing a meshing strategy to divide the computational domain into smaller components for precise simulations of soil-foundation interaction, the numerical model was created in PLAXIS 3D.

Mesh Generation

To guarantee accuracy, a fine mesh was created; a convergence check was done to verify that additional modifications did not significantly change results. The model used 10-node tetrahedral elements, each with 4 Gauss points [10]. The number of elements was modified according to footing size to strike a balance between computational efficiency and correctness.

Boundary Conditions

Custom borders were created to reduce edge effects. Following [9], the vertical depth was set at 10B, and the horizontal plane dimensions were 13B × 13 B. Standard fixities in PLAXIS 3D were used to specify the edges.

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Material Model

Chosen to describe the mechanical behavior of the sandy soil, characterized by a linear elastic-perfectly plastic constitutive relationship, the Mohr-Coulomb (MC) model was applied. Geotechnical studies under various loading circumstances frequently employ this model.

Material Properties

Young's modulus ($E = 50{,}000\ kN/m^2$), Poisson's ratio ($\nu = 0.\ 34$), internal friction angle ($\phi = 39°$), cohesion ($c = 1\ kN/m^2$), and dilatancy angle ($\psi = 9°$) were among the MC model parameters. The concrete footing was modeled as linear elastic with a unit weight (γ) of $24\ kN/m^3$, $E = 25 \times 10^6\ kN/m^2$, and $\nu = 0.\ 15$.

Model Validation

Comparing PLAXIS 3D findings against established research verified the soil model. Literature was the basis for the geotechnical characteristics; to guarantee accuracy, loads were repeated. The validation validated the model's accuracy for predicting bearing capacity.

Full-Scale Foundation Modeling (Study Model)

Four square footings (1 m × 1 m, 2 m × 2 m, 3 m × 3 m, and 4 m × 4 m), each of uniform thickness 0.50 m, were studied to assess the structural behavior under loading.

Parametric Study: Influence of Groundwater Level Variations

The impact of groundwater table (G.W.L) fluctuations on the bearing capacity of shallow foundations was examined using a methodical parametric analysis. The same validated numerical model was used in this study to systematically evaluate the effects of fluctuating groundwater levels on both ultimate and allowable bearing capacities across a range of foundation sizes and embedment depths, building on the work of [9]. Cases with no groundwater influence (baseline condition), groundwater tables at the ground surface (0.00 m), and increasingly deeper levels (0.50 m, 1.00 m, and 1.50 m below the surface) were among the scenarios that were analyzed. Furthermore, there were instances where the groundwater table was situated at 1.0B, 1.5B, and 2.0B (where B stands for the footing width). A thorough assessment of the effects of groundwater fluctuations on bearing capacity in sandy soils, both in relation to the ground surface and foundation base, was made possible by this methodical approach. Finding the allowable design bearing capacity (q_{all}), which is the lowest value between the allowable capacity based on a factor of safety ($q_u/3$) and the capacity corresponding to a settlement limit of 25 mm (S_{25mm}), was the specific focus of the analysis. The study offers vital insights into the role of groundwater conditions in geotechnical design, especially for structures in sandy soil environments where water table fluctuations can significantly influence stability and settlement behavior. This is achieved by methodically varying the groundwater depth and examining the effects on foundation performance.

Results

The bearing capacity of shallow foundations in sandy soils is examined in this study about variations in groundwater level (G.W.L). The analysis focuses on foundations with embedment depths (D_f) between 0.00m and 1.50m and sizes ranging from 1m x 1m to 4m x 4m. The more critical value between settlement-limited capacity (S_{25mm}) and capacity based on safety factor ($q_u/3$) is the allowable design bearing capacity (q_{all}). Key findings by foundation size are presented below:

Foundation Area (1m × 1m):

Table 1: Bearing capacity of 1 m × 1 m under varying groundwater levels (G.W.L) for varying depths.

D_f (m)	G.W.L (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
		q_u	$q_u/3$	S_{25mm}	q_{all}
0.00	**No G.W.L**	1540	513.33	730	513.33
	G.W.L=0.00	1055	351.67	628	351.67
	G.W.L=0.50	1455	485	708	485
	G.W.L= (1.0B)	1540	513.33	730	513.33
	G.W.L= (1.50B)	1540	513.33	730	513.33
	G.W.L= (2.0B)	1540	513.33	730	513.33

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0.50	No G.W.L	4350	1450	1009	1009
	G.W.L=0.00	2900	966.67	906	906
	G.W.L=0.50	3720	1240	950	950
	G.W.L=1.00	4270	1423.33	975	975
	G.W.L= (1.0B)	4310	1436.67	1009	1009
	G.W.L= (1.50B)	4350	1450	1009	1009
	G.W.L= (2.0B)	4350	1450	1009	1009
1.00	No G.W.L	7250	2416.67	1090	1090
	G.W.L=0.00	4580	1526.67	980	980
	G.W.L=0.50	5620	1873.33	1016	1016
	G.W.L=1.00	6440	2146.67	1045	1045
	G.W.L=1.50	6920	2306.67	1065	1065
	G.W.L= (1.0B)	7140	2380	1076	1076
	G.W.L= (1.50B)	7250	2416.67	1090	1090
	G.W.L= (2.0B)	7250	2416.67	1090	1090
1.50	No G.W.L	10300	3433.33	1132	1132
	G.W.L=0.00	6300	2100	1018	1018
	G.W.L=0.50	7850	2616.67	1040	1040
	G.W.L=1.00	8850	2950	1070	1070
	G.W.L=1.50	9750	3250	1095	1095
	G.W.L= (1.0B)	10250	3416.67	1120	1120
	G.W.L= (1.50B)	10300	3433.33	1132	1132
	G.W.L= (2.0B)	10300	3433.33	1132	1132

The largest effects are seen in smaller foundations; at the surface-level water table (G.W.L = 0.00m), bearing capacity drops by 45.97% for surface foundations (D_f=0.00m) and by 11.22% for deeper foundations (D_f=1.50m). Furthermore, when the water table drops to 0.50 meters, the impact drops to 5.84%, but at 1.00 meters, the effects are negligible (no reduction).

2m × 2m Foundations

Table 2: Bearing capacity of 2 m × 2 m under varying groundwater levels (G.W.L) for varying depths.

D_f (m)	G.W.L (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
		q_u	$q_u/3$	S_{25mm}	q_{all}
0.00	No G.W.L	2650	883.33	530	530
	G.W.L=0.00	1720	573.33	477	477
	G.W.L=0.50	2260	753.33	504	504
	G.W.L=1.00	2500	833.33	513	513
	G.W.L=1.50	2570	856.67	519	519
	G.W.L= (1.0B)	2650	883.33	530	530
	G.W.L= (1.50B)	2650	883.33	530	530
	G.W.L= (2.0B)	2650	883.33	530	530
0.50	No G.W.L	6500	2166.67	680	680
	G.W.L=0.00	4060	1353.33	625	625
	G.W.L=0.50	5000	1666.67	637	637
	G.W.L=1.00	5560	1853.33	656	656
	G.W.L=1.50	5940	1980	664	664
	G.W.L= (1.0B)	6460	2153.33	674	674
	G.W.L= (1.50B)	6480	2160	678	678
	G.W.L= (2.0B)	6500	2166.67	680	680
1.00	No G.W.L	9200	3066.67	708	708
	G.W.L=0.00	5500	1833.33	646	646
	G.W.L=0.50	6520	2173.33	662	662
	G.W.L=1.00	7600	2533.33	677	677

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	G.W.L=1.50	8300	2766.67	686	686
	G.W.L= (1.0B)	9220	3073.33	702	702
	G.W.L= (1.50B)	9260	3086.67	706	706
	G.W.L= (2.0B)	9300	3100	706	706
1.50	**No G.W.L**	12900	4300	760	760
	G.W.L=0.00	8200	2733.33	698	698
	G.W.L=0.50	9200	3066.67	708	708
	G.W.L=1.00	10200	3400	724	724
	G.W.L=1.50	10900	3633.33	734	734
	G.W.L= (1.0B)	12800	4266.67	754	754
	G.W.L= (1.50B)	12900	4300	760	760
	G.W.L= (2.0B)	12900	4300	760	760

Larger foundations exhibit greater sensitivity; at G.W.L=0.00m, D_f=0.00m, the maximum reduction is 11.11%; at D_f=1.00m, this effect decreases to 8.88%; additionally, at G.W.L=0.50m, the impact decreases to 5.16%. Figures 3 and 4 illustrate these patterns using comparative graphs.

3m × 3m Foundations

Table 3: Bearing capacity of 3 m × 3 m under varying groundwater levels (G.W.L) for varying depths.

D_f (m)	G.W.L (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
		q_u	$q_u/3$	S_{25mm}	q_{all}
0.00	**No G.W.L**	3520	1173.33	417	417
	G.W.L=0.00	2340	780	384	384
	G.W.L=0.50	2900	966.67	396	396
	G.W.L=1.00	3200	1066.67	402	402
	G.W.L=1.50	3380	1126.67	406	406
	G.W.L= (1.0B)	3520	1173.33	413	413
	G.W.L= (1.50B)	3520	1173.33	417	417
	G.W.L= (2.0B)	3520	1173.33	417	417
0.50	**No G.W.L**	6280	2093.33	464	464
	G.W.L=0.00	3960	1320	424	424
	G.W.L=0.50	4780	1593.33	434	434
	G.W.L=1.00	5320	1773.33	446	446
	G.W.L=1.50	5720	1906.67	452	452
	G.W.L= (1.0B)	6280	2093.33	464	464
	G.W.L= (1.50B)	6280	2093.33	464	464
	G.W.L= (2.0B)	6280	2093.33	464	464
1.00	**No G.W.L**	8500	2833.33	486	486
	G.W.L=0.00	5400	1800	447	447
	G.W.L=0.50	6300	2100	456	456
	G.W.L=1.00	7000	2333.33	464	464
	G.W.L=1.50	7540	2513.33	470	470
	G.W.L= (1.0B)	8500	2833.33	486	486
	G.W.L= (1.50B)	8500	2833.33	486	486
	G.W.L= (2.0B)	8500	2833.33	486	486
1.50	**No G.W.L**	11000	3666.67	515	515
	G.W.L=0.00	6920	2306.67	471	471
	G.W.L=0.50	7820	2606.67	479	479
	G.W.L=1.00	8600	2866.67	489	489
	G.W.L=1.50	9220	3073.33	496	496
	G.W.L= (1.0B)	11000	3666.67	515	515

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	G.W.L= (1.50B)	11000	3666.67	515	515
	G.W.L= (2.0B)	11000	3666.67	515	515

For medium-sized foundations, the worst-case reduction is 8.59% at G.W.L=0.00m, D_f=0.00m, and the effect is 5.30% at G.W.L=0.50m. The data in Figures 5 and 6 support these conclusions.

4m × 4m Foundations:

Table 4: Bearing capacity of 4 m × 4 m under varying groundwater levels (G.W.L) for varying depths.

D_f (m)	G.W.L (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
		q_u	$q_u/3$	S_{25mm}	q_{all}
0.00	No G.W.L	4560	1520	345	345
	G.W.L=0.00	2980	993.33	321	321
	G.W.L=0.50	3550	1183.33	328	328
	G.W.L=1.00	3950	1316.67	333	333
	G.W.L=1.50	4120	1373.33	337	337
	G.W.L= (1.0B)	4560	1520	345	345
	G.W.L= (1.50B)	4560	1520	345	345
	G.W.L= (2.0B)	4560	1520	345	345
0.50	No G.W.L	7100	2366.67	371	371
	G.W.L=0.00	4600	1533.33	346	346
	G.W.L=0.50	5340	1780	352	352
	G.W.L=1.00	5820	1940	357	357
	G.W.L=1.50	6260	2086.67	361	361
	G.W.L= (1.0B)	7100	2366.67	371	371
	G.W.L= (1.50B)	7100	2366.67	371	371
	G.W.L= (2.0B)	7100	2366.67	371	371
1.00	No G.W.L	9960	3320	389	389
	G.W.L=0.00	6220	2073.33	361	361
	G.W.L=0.50	7200	2400	366	366
	G.W.L=1.00	7800	2600	372	372
	G.W.L=1.50	8480	2826.67	376	376
	G.W.L= (1.0B)	9960	3320	389	389
	G.W.L= (1.50B)	9960	3320	389	389
	G.W.L= (2.0B)	9960	3320	389	389
1.50	No G.W.L	12100	4033.33	404	404
	G.W.L=0.00	7560	2520	374	374
	G.W.L=0.50	8520	2840	379	379
	G.W.L=1.00	9280	3093.33	385	385
	G.W.L=1.50	10000	3333.33	390	390
	G.W.L= (1.0B)	12100	4033.33	404	404
	G.W.L= (1.50B)	12100	4033.33	404	404
	G.W.L= (2.0B)	12100	4033.33	404	404

The largest foundations have the highest stability, with a maximum reduction of 7.48% in the worst-case scenario and a drop to 5.18% at G.W.L=0.50m. Figures 7 and 8 visually validate these findings.
The variation in allowable bearing capacity values (shown as a percentage change) due to different groundwater levels (G.W.L) for different foundation sizes is shown in Figure 2. Shallow foundations with depths (D_f) of 0 m, 0.5 m, 1.0 m, and 1.5 m are taken into account in this analysis. There are three comparisons of foundation sizes: 1.0 m versus 2.0 m, 1.0 m versus 3.0 m, and 1.0 m versus 4.0 m.

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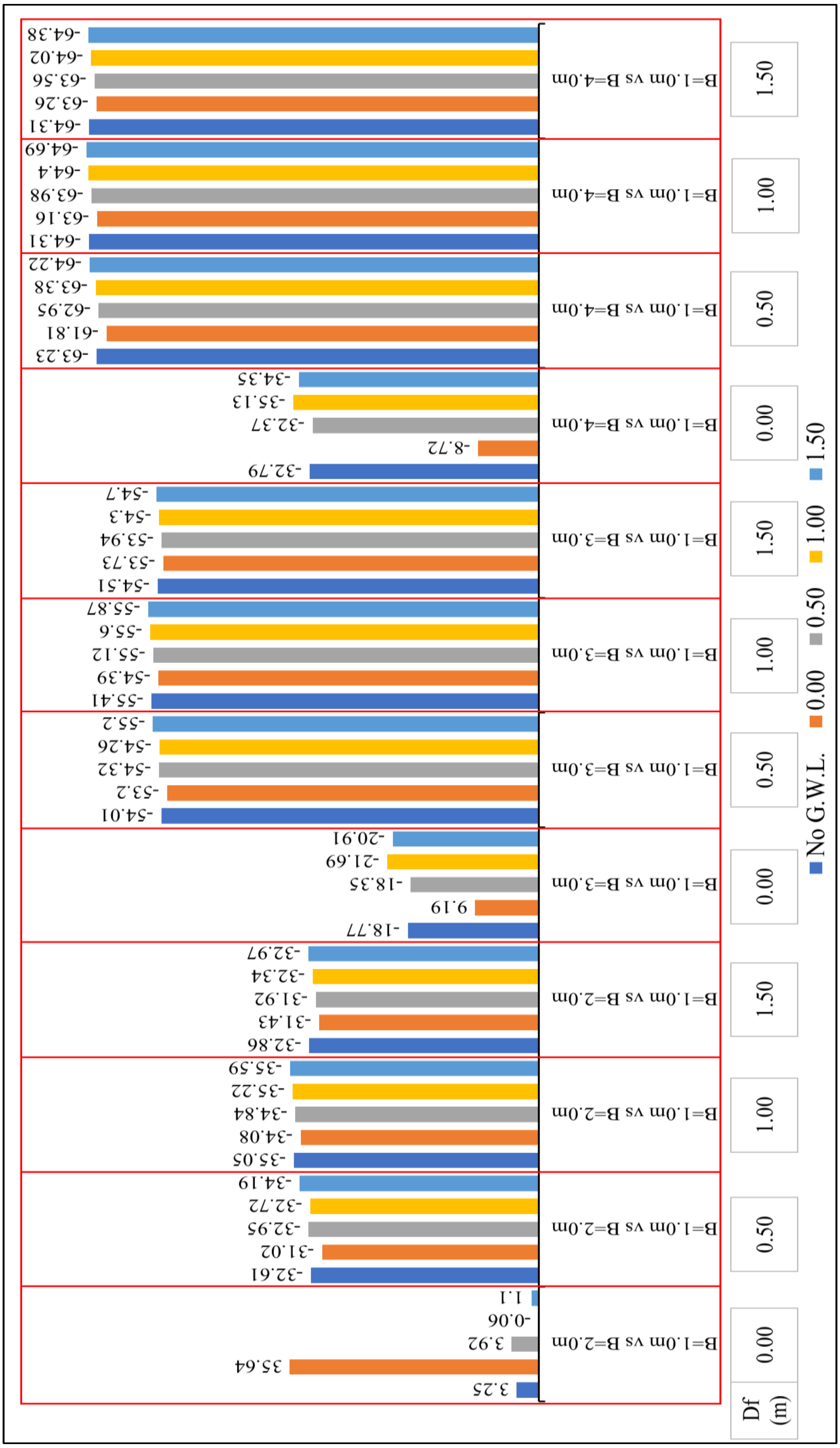

Figure 2. Percentages Difference in Allowable Bearing Capacity for Different Foundations Sizes.

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Discussion

The results show a strong link between groundwater levels and foundation performance, exposing complex interactions that need thorough analysis. One important finding is that smaller foundations (1 m x 1 m) are far more susceptible to groundwater variations than their larger equivalents (4 m × 4 m). This disparity can be explained by the fact that pore water pressure has a disproportionately large impact on smaller foundation areas, where hydraulic forces have a greater relative impact because of the less distributed load. Additionally, the study emphasizes how increased embedment depth (D_f) consistently has a moderating effect for all foundation sizes. The two main benefits of deeper foundations are increased overburden pressure, which increases stability, and less direct contact with saturated zones, which lessens the negative effects of groundwater. This implies that one of the most important design factors for reducing hydrostatic risks in foundation engineering is embedment depth.
Moreover, the findings show a key water table depth threshold, beyond which groundwater affects are insignificant. In particular, negative impacts are effectively mitigated, regardless of foundation size, by keeping a minimum vertical distance of 1.00m between the water table and the foundation base. In settings where groundwater fluctuation is likely to occur, this finding offers a useful guideline for initial design considerations.
The complicated dynamics of soil-structure interaction are indicated by the notable nonlinear relationship between groundwater elevation and bearing capacity decline. The non-linearity suggests that traditional simple models might not fully represent the underlying dynamics, requiring more research into how foundation design, hydraulic conductivity, and soil saturation interact. Predictive frameworks for foundation design under fluctuating groundwater conditions could be improved by future research that examines these relationships using sophisticated numerical models or carefully monitored experimental trials.

Conclusion

This study highlights the crucial connection between foundation performance and groundwater levels. For foundation design in sandy soils, the detailed information in Tables 1-4 and the graphic analysis in Figure 9 offer crucial direction. To guarantee structural safety and optimum performance, engineers must thoroughly assess groundwater conditions.

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