Water Table Effects on the Behaviors of the Reinforced Marine Soil-footing System

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Abstract

This study evaluates the effects of a water table on the behavior of a geogrid reinforced soil-footing system on marine soft soil layers in Qeshm Island, Iran. The main aim of this research is to recommend the optimum specification of the reinforced soil-footing system. A series of geotechnical tests were adopted to measure the properties of the soil profile. The impacts of the water table and the geogrid layer specifications were evaluated by the finite element analysis to investigate the system's behaviors. Finally, the optimal reinforced soil footing is suggested.

Keywords: Finite Element Method; Geogrid Layers; Marine Soil; Reinforced Soil-Footing System; Safety Factor; Water Table.

1. Introduction

The usage of geogrid reinforcement within the soil-footings has recently received considerable attention for several reasons, such as the lack of proper and robust construction sites, i.e., in marine soils with a low bearing capacity [1]. Such a method is considered a cost-effective alternative technique. Increasing the bearing capacity, reducing the settlements, and avoiding the construction of deep and expensive footings are some of this method's consequences [2, 3]. The application of geogrids leads to redistributing the stresses in the soil mass and enhancing the stability of the reinforced soil structures [4]. On the other hand, the size, stiffness, position, tensile strength, and number of geogrid layers have significant effects on the bearing capacity of the reinforced soil-footing systems. There is no standard agreement to simply measure the bearing capacity of a geogrid-reinforced soil footing [5]. However, the bearing capacity of the reinforced strip footing was evaluated systematically [6]. It is worth mentioning that geogrids are geosynthetic products that consist of combinations of longitudinal and transverse ribs, which are divided into uniaxial geogrids and biaxial geogrids [4]. Recently, many numerical and experimental studies have been conducted to evaluate the behavior of geogrid reinforced soil footings. Researchers studied the improvement of the ultimate and allowable bearing capacities of strip footings on the reinforced soil-footings, using various forms of reinforcing materials like metal bars, rope fibers, metal strips, geotextiles, geocells, and geogrids [2, 3, 7–10].

Several laboratory model tests were evaluated to investigate the ultimate bearing capacity of a strip footing on the geogrid reinforced sand and saturated clay [7]. The results show that the settlement of the reinforced and unreinforced soil-footing in clay was almost the same. However, an increase in the ultimate load in the sand increased the settlement. Also, it was suggested that the optimum widths of the geogrid layers were 8 and 5 times the footing widths

in the sand and clay, respectively. The laboratory model tests were presented to measure the ultimate bearing capacity of a strip footing supported by geogrid-reinforced-sand [11]. The bearing capacity ratio in the matter of ultimate load increases with embedment for a given reinforcement depth ratio. A method for measuring the pressure intensity for a rectangular footing located on a reinforced soil-footing was numerically presented [12]. The method has been inferred to find out the ultimate bearing capacity of footing on the reinforced soil. The ultimate bearing capacity of strip footings was investigated [13]. The subsoils including a strong sand layer overlying a low-bearing capacity sand deposit. It was observed that the bearing capacity increased, and the settlements were reduced. A solution for estimating the ultimate bearing capacity of geogrid reinforced soil-footing in sand and silty clay soils was experimentally and numerically presented [14]. The predicted bearing capacity agreed well with the experimental results. The geogrid reinforced soil-footing model was numerically improved [4].

The model uses the Eulerian technique, combined with the coupled Eulerian-Lagrangian method to dissect the interaction in the related numerical model. The suggested numerical method was selected as a referential value for geogrid reinforced soil-footing analysis. The ultimate bearing capacity of strip footings on reinforced soil-footings was numerically developed [2]. The depth of the shear failure zone depends on the relative strength of the reinforced soil layer and the underlying unreinforced soil. A numerical method was proposed to determine the bearing capacity of strip footings on the reinforced sand-footing [5]. The bearing capacity determined for the extended reinforcement was 1.23 times greater than the bearing capacity obtained from the short reinforcement length equal to footing width. Furthermore, there was no difference perceived for a reinforcement length above four times the footing width. The effects of the position and the number of the geotextile layers on the bearing capacity of the reinforced soil-footing were experimentally and numerically investigated [15]. The bearing capacity was increased by the implementation of geotextile layers. Also, increasing the geotextile layers would not necessarily lead to increasing the bearing capacity of the reinforced soil-footing system. A new practical reinforcement technique by adopting geosynthetics to increase the bearing capacity of a shallow footing located on the sand was numerically developed [3]. It was observed that the full wraparound end solution gave a noticeable improvement in the bearing capacity and needed a lesser quantity of geotextile layers.

Almost all the previous studies have focused on improving the bearing capacity of soil layers using reinforcing materials. In contrast, few studies are related to the safety factor of the reinforced soil-footing systems. On the other hand, due to the erratic fluctuations of the water table in marine and coastal areas, improving the strength and stability of such weak marine soils is vital. Therefore, in this study, a numerical analysis was carried out to evaluate the settlement and the safety factor of the reinforced marine soil-footing in Qeshm Island, Iran.

2. Site Description and the Geotechnical Properties of the Island

As illustrated in Figure 1, Qeshm Island (26º 55' N; 56º 10' E) is located a few kilometers off the southern coast of Iran in the Persian Gulf and lies strategically in the Strait of Hormuz [10].

Figure 1. Location of Qeshm Island in Iran

Soil samples at the 1-meter interval to a depth of 15 m were obtained using an auger. A series of in-situ and laboratory tests were conducted to measure the geotechnical properties of the site [16]. Table 1 summarizes the geotechnical properties of the soil layers of the site. It should be noted that the water table was seen at a depth of 1.5 m below the ground surface.

Table 1. Geotechnical properties of the soil layers

Depth (m)	Passing Sieve (%)		Soil and Lithology Description	G	C (kPa)	φ (degree)	E (MPa)	LL (%)	PI (%)	Moisture (%)	γ_sat (gr/cm³)	SPT (N)			
	4	200										15 cm	15 cm	15 cm	30 cm
1 2	100	52.8	ML (Sandy Silt)	2.66	3	27.1	22	NL	NP	17.2	1.83	3	4	5	9
3 4	100	84.8			5	25.9	22	NL	NP	22.6	1.91	2	2	2	4
5 6	100	87.9	CL-ML (Silty Clay)	2.70	8	25.1	20	27	6	21.4	1.91	3	3	4	7
7 8	100	89.3	CL (Lean Clay)	2.73	14	23.9	19	39	22	23.2	1.95	3	5	8	13
9 10 11	100	86.3			17	22.6	19	37	18	23.6	1.95	4	7	8	15
12 13	100	100	CL (Lean Clay)	2.75	21	21.8	19	42	25	24.5	1.99	19	25	33	>50
14 15	100	98.5			18	23.4	19	43	20	24.4	1.99	21	27	35	>50
Test / *ASTM*	[17]			[18]	[19]		[20]	[21]	[21]	[22]	[23]	[24]			

3. Numerical Simulation and Constitutive Models

The main aim of this research is to evaluate the effects of the water table changes (WT/B) on the settlement and the safety factor (SF) of the reinforced loose marine soil-footing system. *Plaxis 2D, Finite Element Method* was conducted for this study. The behavior of the soil layers was considered as Mohr-Coulomb plasticity. First geogrid layer spacing from the ground surface (u), geogrid layer spacing (h), geogrid layer lengths (b), geogrid layer numbers (n), and geogrid tensile strengths (S_t), are investigated (Figure 2). Width, normal stiffness (EA), flexural rigidity (EI), thickness (d), weight (w), and the Poisson's ratio (v) of the footing were taken as 6 m, 1.725×10^7 kN/m, 3.591×10^5 kNm²/m, 0.5 m, 12 kN/m/m and 0.2, respectively. As shown in Figure 2, the horizontal width and a vertical thickness of 160 m and 45 m, used for simulation, respectively. The bottom boundary was fully fixed ($u_x=u_y=0$) while solely the horizontal movements of both sides were fixed ($u_x=0$). The ground surface was free to move in all directions.
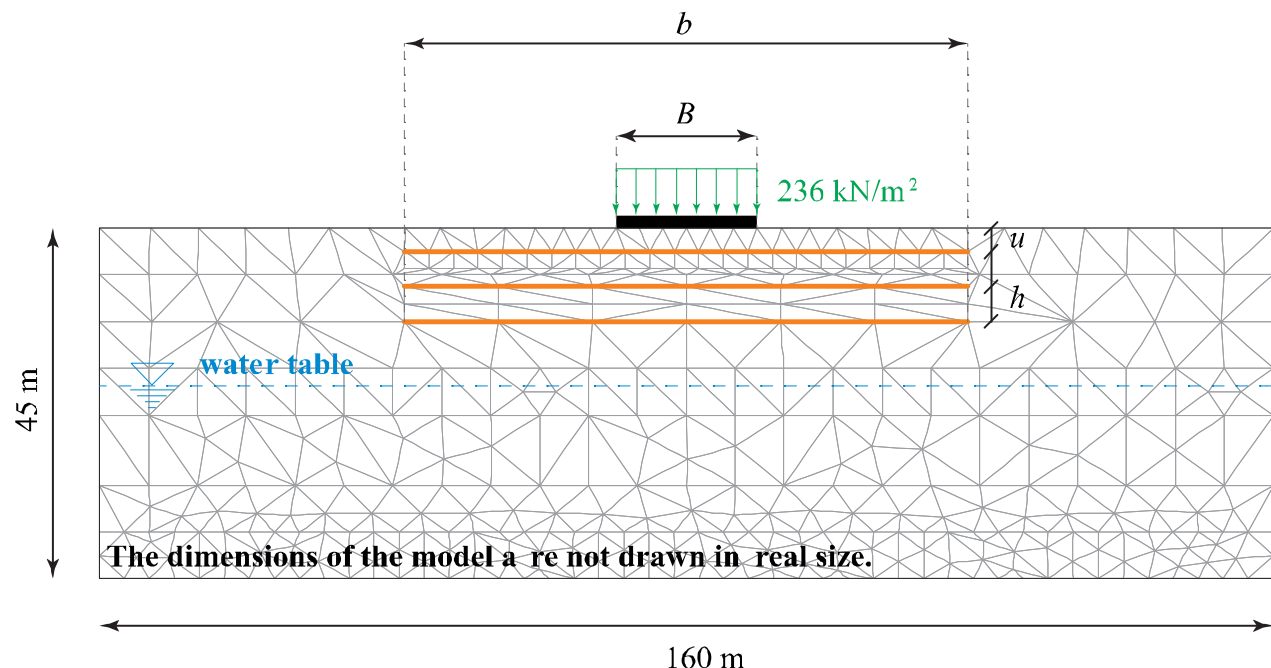

Figure 2. Finite element meshes with boundary conditions

The tangent intersections in elastic and plastic areas in load-settlement curves were the criterion for calculating the bearing capacity of the footing [25–30]. The load equal to 236 kN/m^2 was the calculated bearing capacity for the unreinforced soil-footing system in the dry condition. This value was considered in all numerical simulations for investigating the system's behaviors to eliminate the effect of the load values and determine the reasonable load applied on the footing.

It is worth adding that the geogrid specifications (u, h, b, n, S_t) are selected based on the project's site limitations. The optimum specification of the geogrid layers is just sufficient to meet the target safety factor. The globe safety factor of the reinforced soil-footing system can be estimated by the strength reduction algorithm. However, the optimum geogrid layer properties cannot be obtained directly, and thus, a series of trial analyses with different conditions were conducted in the parametric study [31].

4. Results and Discussion

4.1. Comparison with other Researches

There are minimal experimental and analytical studies on the safety factor of the reinforced soil-footing system. Most of the studies have focused on the bearing capacity of these systems. Yoo (2001) [32] experimentally performed model tests to study the bearing capacity of a strip footing located on a sandy soil slope reinforced with geogrid layers. On the other hand, Rostami and Ghazavi [33] analytically compared the experimental results reported by Yoo (2001) [32] as presented in Table 2. In their studies, the increase in the ultimate bearing capacity due to the adoption of the reinforcement has been expressed in the form of bearing capacity ratio ($BCR=q_{uR}/q_u$) as a non-dimensional term. q_{uR} is the ultimate bearing capacity of the footing on the reinforced soil-footing system, and q_u is the ultimate bearing capacity of the same unreinforced system. The ultimate bearing capacity was defined as the vertical load corresponding to the footing settlement reached 10% of the footing width.
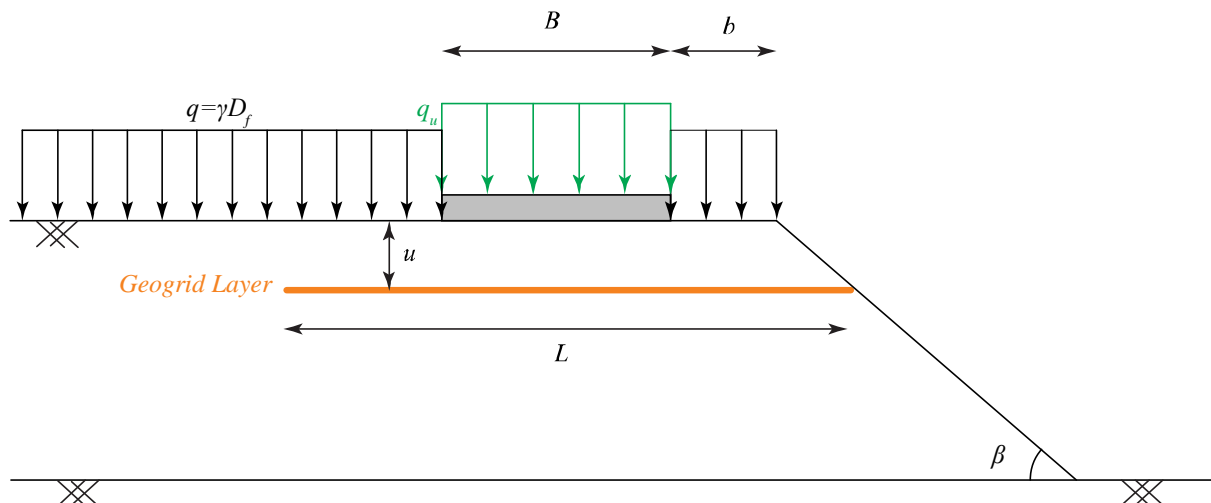

Figure 3. The geometry of reinforced soil-footing system

As shown in Table 2, the simulated results of this study are in good agreement with laboratory and analytical model tests [32, 33].

Table 2. A Comparison between the calculated bearing capacity ratio with analytical and experimental model tests

Number of geogrid layers	Present study	Yoo (2001) [32]	Rostami and Ghazavi (2015) [33]
1	1.65	1.50	1.10
2	2.10	2.20	2.00
3	3.50	3.30	3.25

The specification of the model: u/B=0.3, L/B=4.5, h/B=0.3, b/B=1, and S_t=55 kN/m

4.2. Parametric Study

Figure 4 to Figure 8 show the safety factor and the settlement of the reinforced soil-footing system versus WT/B. Different parameters (u, h, b, n, S_t) have been evaluated in the following parametric studies to reach the optimum reinforcement specification.

First Geogrid Layer Spacing from the Ground Surface (*u*)

Figure 4 shows the settlement and the safety factor of the reinforced soil-footing system due to *WT*/B and *u* changes. By increasing the *WT*/B, the settlement decreased dramatically. Also, by reducing *u*, the settlement remained unchanged. It is also clear that for the unreinforced soil-footing systems, the maximum settlement was lower than those of the reinforced ones. Adoption of geogrid layers results in making the soils a solid and uniform mass. Therefore, it leads to providing symmetric settlements. It is evident that by reinforcing the soil-footing system, the safety factor increased significantly. For example, for *WT*/B≥2, the safety factor of the unreinforced and reinforced systems with *u*=0.5, 1, and 2 m, were 1.32, 1.36, 1.53, and 1.40, respectively. Consequently, for *WT*/B≥2 and *u*=1 m, the safety factor of the reinforced system was almost 15% higher than the unreinforced systems. Also, the safety factor increased by increasing *WT*/B. For example, for the reinforced system with *u*=1 m, the safety factor increased from 1.32 to 1.53 by increasing *WT*/B.

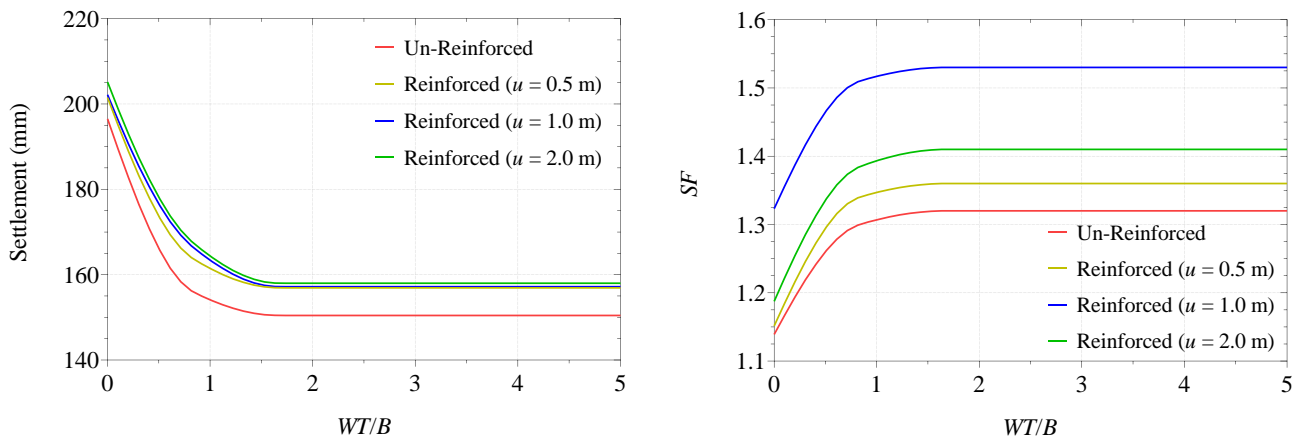**Figure 4. The settlement and the safety factors of the soil-footing system due to the changes of WT/B and u (for all tests: h=0.5 m, b=12 m, n=3, and St=50 kN/m)**

Geogrid Layer Spacing (*h*)

Figure 5 shows the settlement and the safety factor of the reinforced soil-footing system due to the changes of *WT/B* and *h*. By increasing *h* from 0.5 to 1 m, the settlement of the reinforced soil-footing system remained almost unchanged. By increasing *WT/B* from 0 to 5, the settlement decreased significantly at first, which led to a plateau when *WT/B*≥1.5. Also, the settlement of the unreinforced soil-footing system had been just under the values of the reinforced one. On the other hand, the safety factors of the unreinforced and reinforced soil-footing system with *h*=0.5 m, were almost similar. However, they were significantly less than those of the values of the reinforced systems with *h*=0.75 and 1 m (Figure 5). It can be attributed to the lack of geogrid layer in lower zones. For instance, for *WT/B*=0.8 and *h*=0.5, 0.75 and 1 m, the safety factor of the unreinforced and reinforced soil-footing system was 1.14, 1.15, 1.23, and 1.18, respectively. Therefore, the geogrid layer spacing had negligible effects on the safety factor for *WT/B*=0.
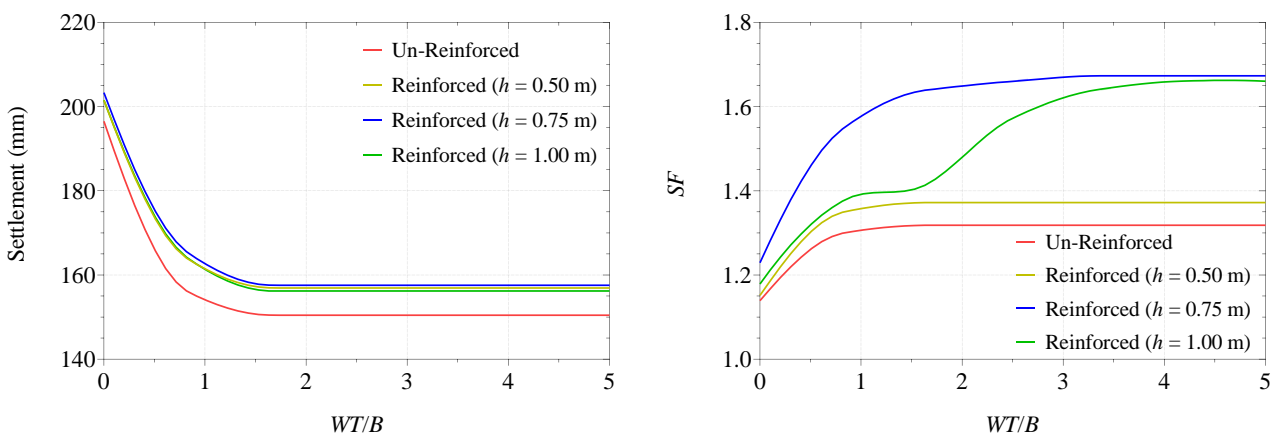

Figure 5. The settlement and the safety factors of the soil-footing system due to the changes of WT/B and h (for all tests: u=0.5 m, b=12 m, n=3, and St=50 kN/m)

Geogrid Layer Length (*b*)

Figure 6 illustrates the settlement of the reinforced soil-footing system and the safety factor due to the changes of *WT/B* and *b*. By increasing *WT/B* from 0 to 5, the settlement decreased significantly, which led to a plateau in *WT/B*=1. The settlement of the unreinforced soil-footing system was well below the values of the reinforced one. For instance, for *WT/B*≥2 and *b*=24 m, the settlement of the unreinforced soil-footing system and the reinforced one were 150.47 and 156.05 mm, respectively. Generally, by increasing the length of the geogrid layers, the settlement would increase. The length of the geogrid layer had moderate effects on the safety factor; i.e., for *WT/B*≥2 and *b*=24, 18, and 12 m, the safety factor of the reinforced soil-footing system was 1.38, 1.34, and 1.36, respectively; which were 1.05, 1.02, and 1.03 times more than that of the unreinforced system, respectively. *b*=24 m provided the highest footing safety factor as it could induce higher shear properties to the mass. Also, for *WT/B*≥1.5, the safety factor remained almost unchanged. As an illustration, for *WT/B*=0.8 and *WT/B*=5, the safety factor in the case that *b*=24 m was 1.3551 and 1.38, respectively.

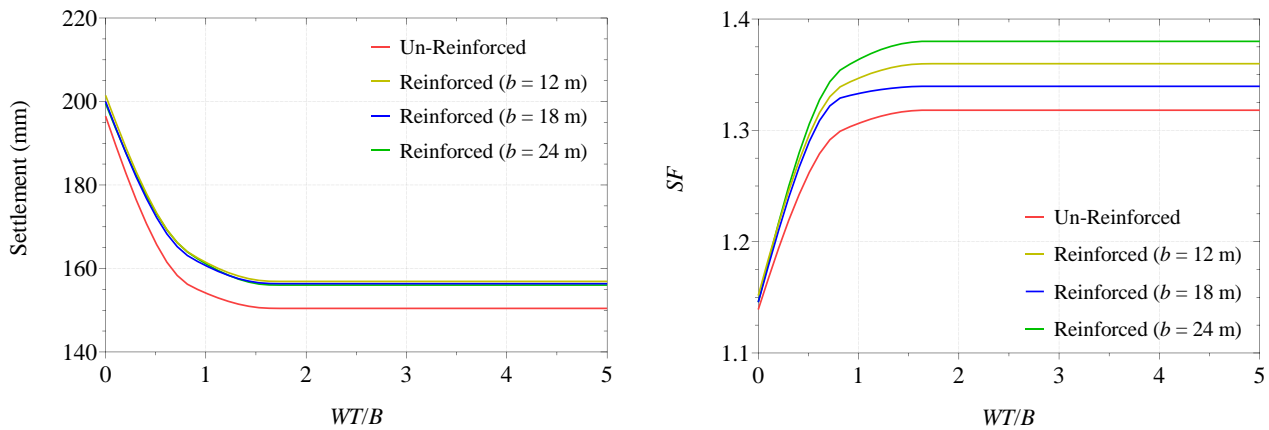**Figure 6. The settlement and the safety factors of the soil-footing system due to the changes of WT/B and b (for all tests: u=0.5 m, h=0.5 m, n=3, and St=50 kN/m)**

Geogrid Layers Number (*n*)

Figure 7 provides the settlement and the safety factor of the reinforced soil-footing system due to *WT/B* and *n* changes. By increasing *WT/B*, the settlement decreased exponentially. The settlement remained approximately unchanged by increasing the number of geogrid layers. Comparing the settlement results, it can be observed that the settlement with *n*=3 was just over the settlement values for the footing with *n*=4 and 5. Reinforcing the soil-footing system with 4 and 5 geogrid layers provided almost the same safety factor. Also, the unreinforced system and reinforced one with *n*=3 caused similar safety factor, significantly less than the safety factor of the soil-footing systems reinforced with 4 or 5 geogrid layers. It could be attributed to the lack of geogrid layer in lower zones. For instance, for *WT/B*≥1.5, the safety factor of the unreinforced and reinforced soil-footing system with 3, 4, and 5 geogrid layers were 1.32, 1.37, 1.70, and 1.79, respectively. Therefore, the geogrid layer length had moderate effects on the safety factor. On the other hand, for *WT/B*≥1, the safety factor reached a plateau. To demonstrate, for *n*=5, when *WT/B*=0.8 and 5, the safety factor was 1.77 and 1.78, respectively.

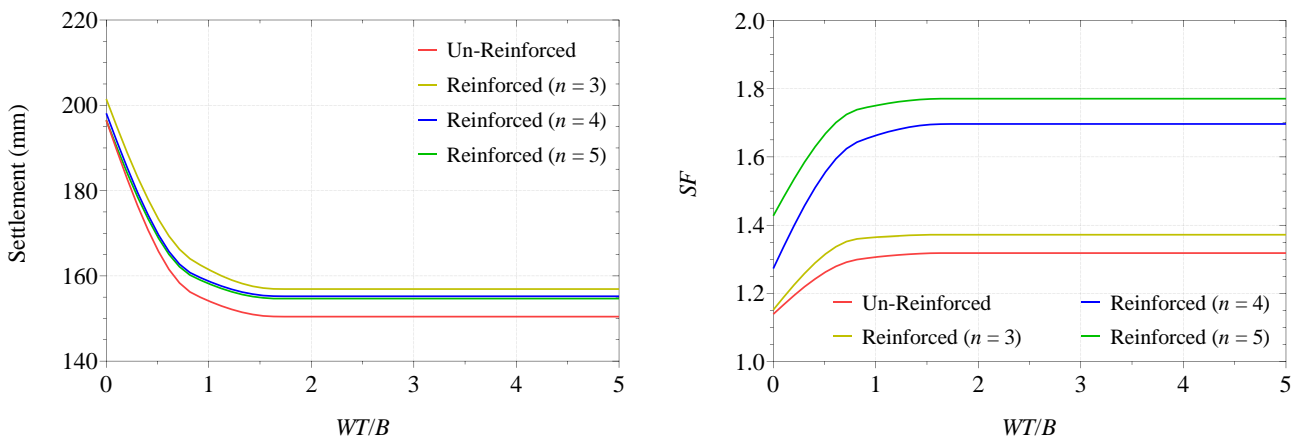**Figure 7. The settlement and the safety factors of the soil-footing system due to the changes of WT/B and n (for all tests: u=0.5 m, h=0.5 m, b=12 m, and St=50 kN/m)**

Geogrid Tensile Strength (S_t)

Figure 8 depicts the settlement and the safety factor of the reinforced soil-footing system due to both *WT/B* and S_t changes. By increasing *WT/B* from 0 to around 1.5, the settlement plunged enormously then remained unchanged by further increasing *WT/B*. The settlement of the system with S_t=50 and 100 kN/m, were higher than that of the system with S_t=200 kN/m. It can be inferred from Figure 8 that the safety factor also increased by increasing S_t. As an illustration, when *WT/B*=0, the safety factor increased from 1.15 to 1.27 by increasing S_t from 50 to 200 kN/m, which increased by 10.24%. It can also be noted that the safety factor of the unreinforced soil-footing system was 1.139 when *WT/B*=0. Moreover, reinforcing the soil-footing system with S_t=100 and 200 kN/m would provide similar values of the safety factor. Also, the safety factor of the unreinforced and reinforced soil-footing system with S_t=50 kN/m had almost identical values, which were enormously less than those of the reinforced systems with S_t=100 and 200 kN/m. For instance, when *WT/B*≥1.5, the safety factor of the unreinforced and reinforced systems with S_t=50, 100, and 200 kN/m, were 1.32, 1.36, 1.57, and 1.67, respectively.
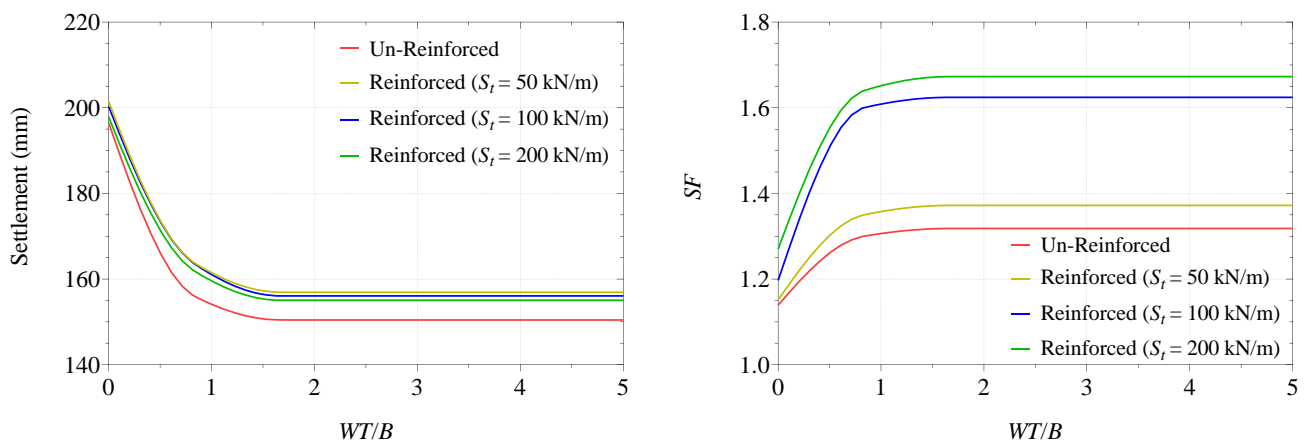

Figure 8. The settlement and the safety factors of the soil-footing system due to the changes of WT/B and St (for all tests: u=0.5 m, h=0.5 m, b=12 m, and n=3)

4.3. Optimum Reinforcement Specification

The main aim of this paper is to recommend an optimal reinforcement specification based on the highest safety factors evaluated in the parametric study (i.e., *u*, *h*, *b*, *n*, S_t). According to the achieved results, *u*=1 m, *h*=0.75 m, *b*=24 m, *n*=5, and S_t=200 kN/m, are the optimum values for the reinforced soil-footing system. Figure 9 compares the settlement and the safety factor of the unreinforced and the optimum reinforced soil-footing systems. As shown in Figure 9, it is evident that the safety factor of the optimum reinforced soil-footing system increases by about 32% to 38% for *WT/B* ≥1 and *WT/B* =0, respectively. It should be noted, no significant changes are observed in the settlement by reinforcing the soil-footing system.
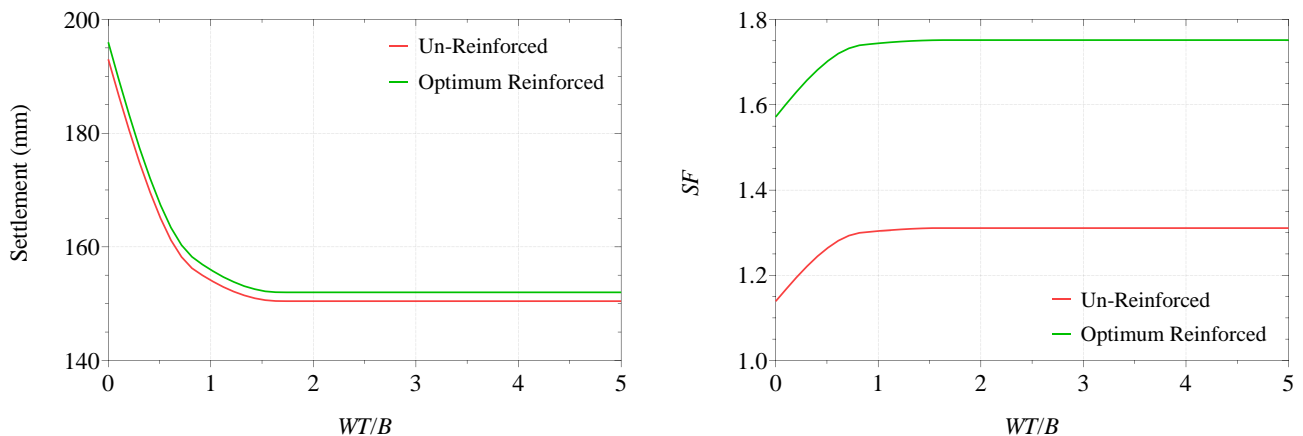

Figure 9. Comparison of the settlement and the safety factor of the soil-footing system in various WT/B for the optimum reinforcement specification

5. Conclusion

This paper was aimed at evaluating the effects of the water table changes on the settlement and the safety factor of a geogrid reinforced soil-footing system on loose marine soils in Qeshm Island, Iran. The following results could be drawn from the numerical analyses:

- Water tables had a significant impact on the behavior of the soil-footing systems. By decreasing the water table, the settlement decreased while the safety factor of the soil-footing system increased.

- By increasing the first geogrid layer spacing from the ground surface (u), the settlement of the reinforced soil-footing system increased. However, by increasing the first geogrid layer spacing from the ground surface from 0.5 to 1 m, the footing safety factor increased. It decreased by increasing the first geogrid spacing from 1 to 2 m.

- By increasing the geogrid layer spacing (h) from 0.5 to 1 m, the settlement of the reinforced soil footing remained almost unchanged. On the other hand, the safety factor of the unreinforced and reinforced soil-footings systems with geogrid layer spacing of 0.5 m was almost similar. However, they were significantly less than those of the values of the reinforced systems with h=0.75 and 1 m

- Increasing the geogrid length (b) led to decreasing the settlement of the soil-footing system. However, by increasing b from 12 to 18 m, the footing safety factor decreased, and then it increased by increasing b from 18 to 24 m.

- The footing settlement increased by increasing the geogrid layer numbers (n). Also, the safety factor of the soil-footing system was increased significantly by increasing the geogrid layer numbers.

- Increasing the tensile strength (S_t) of the geogrid layer resulted in decreasing the soil-footing system settlement and improving the safety factor of the system.

- According to the results, u=1 m, h=0.75 m, b=24 m, n=5, and S_t=200 kN/m are the optimum values for the reinforced soil-footing system.

6. Declarations

6.1. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.2. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.3. Institutional Review Board Statement

Not applicable.

6.4. Informed Consent Statement

Not applicable.

6.5. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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