Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 04, April, 2024

Utilization of Sand Cushion for Stabilization of Peat Layer Considering Dynamic Response of Compaction

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Received 11 October 2023; Revised 15 March 2024; Accepted 20 March 2024; Published 01 April 2024

Abstract

Soft peat soils are located in many zones and at a given depth all over the world and are characterized by their low shear strength and high settlement. It can also cause progressive failure of roads, embankments, and foundations. Sand cushioning is the most beneficial technique used to relieve the stress transmitted to the peat layer to mitigate any deformation and shear failure. In this research, a field study of a road with a soft peat layer located at a depth 4m below the ground surface is carried out. The plate load test is conducted on three cases over the peat layer using sand cushions with and without reinforcement. The results were compared with plate footing on the surface of the road without stabilization. The field tests of the improved technique were verified and deeply analyzed using the numerical program Plaxis. The finite element analysis mainly sheds light on the simulation of the dynamic response that represents the compaction of the sand cushion over the peat layer. A series of numerical models has been done considering the effect of repeated load compaction on the adopted sand cushions with and without reinforcement. The numerical analysis is directed to show the effect of repeated loads of compaction equipment that were used on decreasing the stress over the peat layer. The results showed that the composite compacted cushion with both a higher number of cycles and stress has a great effect on relieving the stresses transmitted to the face of the peat. As a result, the footing capacity is increased with less deformation.

Keywords: Plate Load Test; Geotextile; Repeated Load; Compaction; Sand Cushion.

1. Introduction

Geotechnical engineering names any soil that contains organic matter (plants or animals) organic soil when the organic matter represents less than 25% of its content, muck when the content range of organic matter is between 25% to 75%, and called a peat when the organic matter represents 75% or more of its content. Due to the high content of organic matter, they are distinguished by a dark brown to black color, a spongy consistency, a high initial void ratio, low bulk density, high natural water content, high initial permeability, low shear strength, and high compressibility [1, 2].

The geotechnical characteristics of peat have been studied by Hobbs (1986) [3], Edil & Dhowian (1981) [4], and Edil (2003) [5]. An extensive investigation has been carried out to study the best technique to improve the geotechnical properties of peat, for example, by using cement or a different binder and deep mixing methods [6–8]. Also, fiber-polyester and shredded rubber-crumb as reinforcement materials were adopted for treating peat [9–11]. Heneash et al.

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http://dx.doi.org/10.28991/CEJ-2024-010-04-011

(2023) [12] investigated how the addition of polymer (SBS) improves the qualities of the problematic soil. To attain this goal, experimental programming was planned and conducted on the treated and untreated samples of two types of soils: collapsing silty-sand soil and poor fine-sand soil. Whereas Šiukščius et al. [13] used the geogrid for the application of road subgrade stabilization for pavement evenness. A load load test on stabilized peat subgrade was investigated in the field using geogrid reinforcement within the gravel fills, as stated by Jarrett [14]. It can be seen that the existence of such a reinforced layer significantly reduced the vertical stresses below the reinforced section, and the load was effectively distributed over a wider region.

Mooney et al. [15] stated that the dynamic effect roller relatively decayed when the cyclic responses to soil mass reached 10% of their peak value. Fathi et al. [16] studied numerically in the laboratory and conducted a field measurement to determine the depth of influence of the roller. The obtained results from a wide range of materials indicate that the average depth of influence is 1.80 m, which varies from 1.4 m to 2.2 m.

Adams & Collin [17] studied the behavior of a large-scale model of spread footing load tests on geosynthetic reinforcement to show their beneficial consequences on load transfer technique. This technique of reinforced sections over soft layers can be considered a good method to reduce permanent deformation and stresses that are transmitted to the soft peat layer. Regarding methods of peat stabilization in the literature, which are characterized by a variety of techniques that are applied in the laboratory as small-scale model tests, it can be concluded that there is a lack of knowledge in investigating the large scale in the field to simulate the real behavior of the problem of foundation on the soft peat layer, which is widely tested in the laboratory by different researchers. Basha et al. [18] conducted a series of small-scale model tests to examine the subgrade reaction of the effectiveness of recycled concrete aggregate (RC) in improving the structural performance of sandy soil. Plate bearing experiments were carried out using a footing model (250×250 mm) inside a tank (1500×1500×1000 mm) to determine the stress-strain response, bearing capacity ratio (BCR), ultimate bearing capacity, and modulus of elasticity of the studied mixture. The results demonstrated that the method used to mix the RC with the sand is outstanding and suitable for use in the field.

Therefore, in this research, full-scale field loading tests for two techniques of ground improvement to stabilize a soft peat layer in the site have been carried out in the field to determine the field real load capacity. Afterward, these techniques were verified and further analyzed using finite element analysis using Plaxis 2d. The numerical study helped in better understanding the mechanism of improvement and stress distribution control that transmitted to the soft peat layer in the site. It also shed light on the failure mechanisms and deformation characteristics of reinforced and peat layers. Also, this research presents a novel simulation of sand cushions using dynamic loads to show their beneficial effect on improving the peat layer.

2. Sites and Soil Nature

The investigated site is located in Kafr El-Sheikh Governorate, for the main road in Sidi Salm city, Kafr El-Sheikh governorate, Egypt. A number of five borings are carried out to illustrate the geological nature of soil formation and soil profile, where their depth is extended up to f 10 m for the road. Table 1 presents the soil profile related to the ground sampling that was obtained at the site. The subsoil was composed of a layer of fill to level -0.50m below the ground surface, followed by medium-stiff brown clay extended to level -4.00 m. A layer of dark gray peat layer with thickness of 1m (-5.00 m) underneath gray medium silty clay until a level of -10.00 m. A series of laboratory tests were done to obtain the main geotechnical properties of each layer, as shown in Table 1. The ground water table is found to be at -2.00 m below the ground surface.

Table 1. Physical and geotechnical properties of the soil layer in the site

Depth, m	Soil stratification	Sand%	Clay%	Silt%	Wc%	L.L%	PL%	PI%	Cohesion C kN/m^2	Cc	ϕ	Bulk Unit weight kN/m^3
0-0.5	Fill					NA						16
0.5-4	Brown medium stiff clay	0	93	7	29	50	25	25	40	0.17	-	18.1
4-5	Dark gray peat	0	20	80	450	76	47	29	15	0.46	-	9.81
5-10	Brown medium stiff clay	0	93	7	29	50	25	25	40	0.17	-	18.1

where; Wc is the water content, LL is the liquid limit, PL is the plastic limit, PI is plasticity index, Cc is the coefficient of graduation and ϕ is the angle of internal friction.

Special care has been considered during the extraction of the peat samples to be tested in bulk. Duraisamy et al. (2007, 2009) [11, 19] provided and made up a hand auger as a sampler (UPM sampler) to gather undisturbed peat samples as presented in Figure 1. This adopted sampler met the supplies for an undisturbed sampler's requirement or specification.

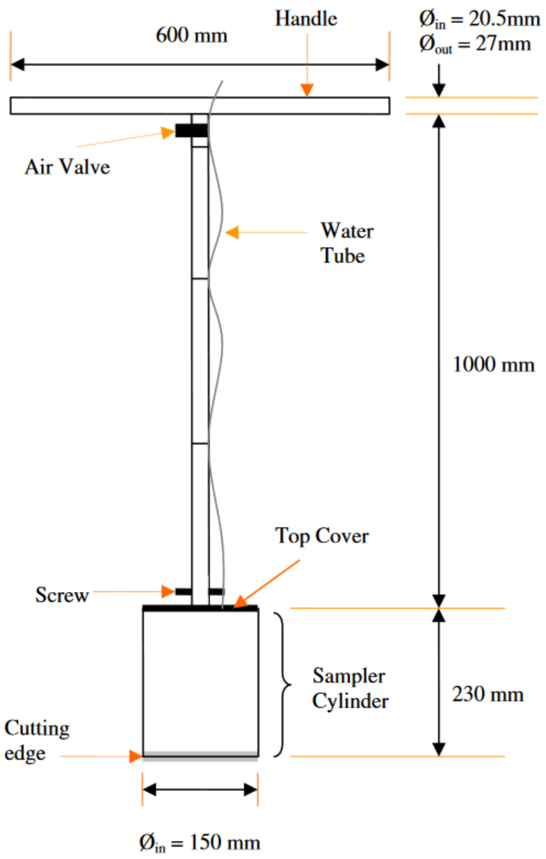

Figure 1. Peat sampler in the site [11]

The physical characteristics of the peat layer, which causes a failure of roads and pavement in the form of excessive settlement and road deformation, are shown in Table 2.

Table 2. Main properties of tested peat tested in this research

Property	
Decomposition degree %	Highly decomposed peat is higher than 40%.
Unit weight/ Bulk density kN/m^3	9.81
Specific gravity (Gs)	1.47
Organic content %	77
Hydraulic conductivity m/day	0.49

3. Strategy of the Field Study

The most important purpose of the existing study was to inspect the static load-deformation behavior of bearing capacity and settlement of surface plate loading tests at different cases of subgrade. In the case of normal ground without improvement, in the case of using a stabilized layer with a given depth (H) using compacted sand fill, and finally in the case of reinforced mattress composites constructed above peat subgrades. In addition, assess the behavior of geo-composites subgrade above the peat by comparing the test results with those obtained for unreinforced sections and compacted sand bases reinforced with a single layer of geotextile.

3.1. Plate Load Test

The ultimate bearing capacity at the site has been obtained according to the ASTM D1195 [20] Standard Test Method for static plate load tests of soils and flexible pavement.

A series of plate loading tests (PLTs) were carried out by a circular steel plate with a diameter of 0.60 m on a 0.50 m compacted subgrade layer with and without reinforcement in the site for the examined road in different cases. The results were compared with a normal plate load test at the surface of plain ground. The static PLT technique was adopted according to ASTM D1194 [21].

The studied strategy in the field and the tested parameters are illustrated in Figure 2. Figure 2-a shows the load test of the normal case when the plate load is placed directly above the fill without stabilization for comparison. Figure 2-b provides the case of using a compacted fill of a sand layer 0.50 m thick, which is installed in 2 layers (250 mm) as a sand cushion. Each layer was compacted well according to specification (ASTM D 1556-ASTM [22]) to reach the maximum dry density. The granular sand cushion adopted in this investigation was made from dry sand. It was classified according to sieve analysis as well-graded sand. It has a maximum and minimum unit weight of 18.3 and 16 kN/m^3, respectively.

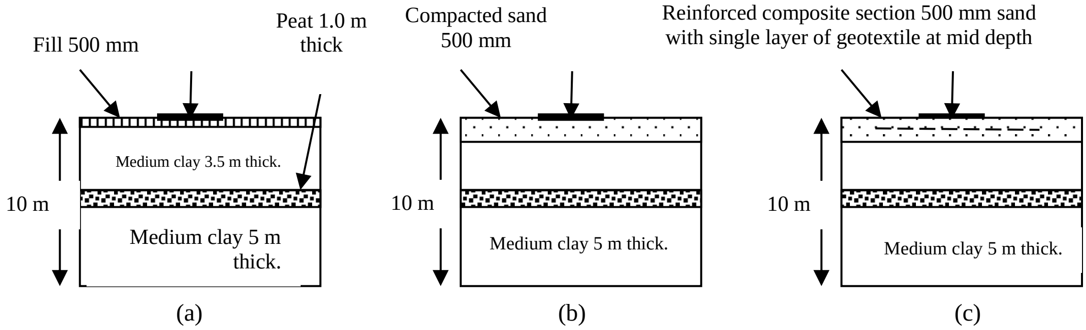

Figure 2. Plate load test for different cases in the field, a: load test on normal ground above the fill, b: load test on stabilized ground above the peat using 500mm compacted fill without reinforcement, c: load test on stabilized ground above the peat using 50.

Figure 3 shows the compaction curve for the tested sand use for stabilization in the site and mention to the optimum moisture content. The specific gravity of the adopted sand is found to be 2.62 and the maximum angle of internal friction is 41^o. The compaction efficiency was checked in the site using sand cone test which is found to be 98%. The final case of study is used a single layer of geotextile at mid depth of sand cushion. The reinforced element used in the field was non-woven geotextile (a heat bonded Typar-3857) that made of polypropylene multifilament fibers. According to data of the manufacturer's, it has a thickness of 2 mm and weight per unit area of 290g/m^2. The elongation at maximum load is 10% that corresponding to tensile strength from the strip test method of 20.1 kN/m. The length of the geotextile was taken thee time of plate diameter (3d) [23, 24].

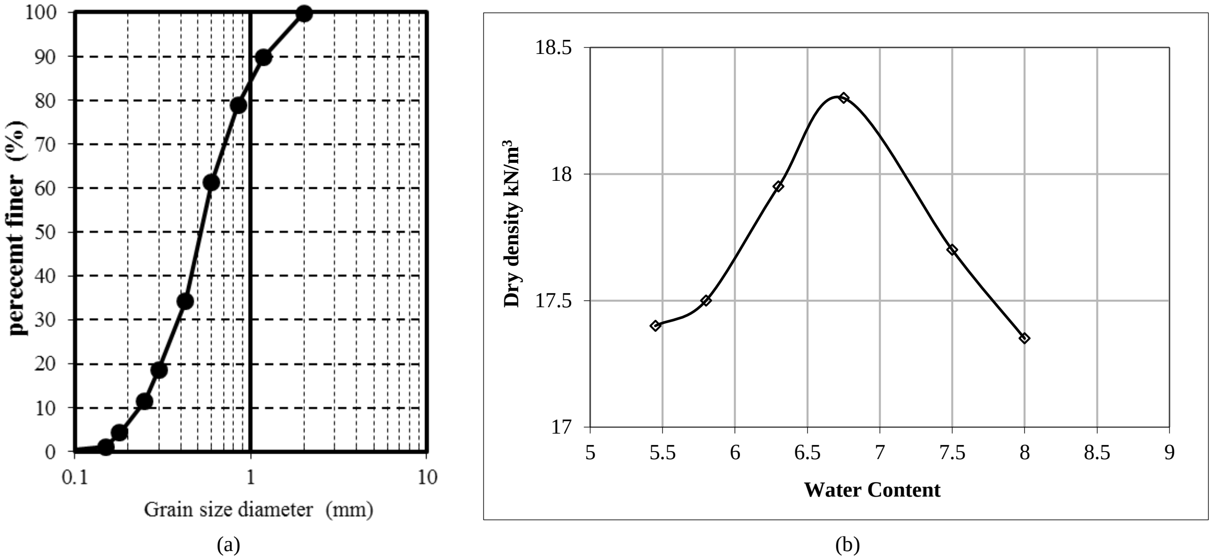

Figure 3. properties of sand cushion a) graduation curve, b) Compaction curve for used sand in the field

4. Field Results and Discussion

4.1. Definition Failure Load and Ultimate Bearing Capacity

In this study, the definition of the ultimate bearing capacity at failure was distinct as the tangent intersection between the initial, straighter segment of the loading-stress-settlement curve and the next steeper, straight part of the curve [17].

4.2. The Stress Settlement Curves

The stress settlement data are provided for the given field tests and presented in Figure 3. It presents the stress settlement curves for plate footing on the surface of fill and pate footing on sand cushions with and without reinforcement. It has been noticed that the stress settlement curves were considerably modified and increased as the subgrade layer was stabilized with sand cushion. It can be seen that for the footing located directly at the surface without stabilization, the bearing capacity is found to be 35 kN/m^2 at a settlement ratio of S/d = 2.17% (d is the plate diameter). While for the stabilized case using a sand cushion with a depth of 50cm without reinforcement, the stress settlement is improved. The existence of such a sand cushion can improve and increase the ultimate bearing capacity compared with plate footing on normal ground. The ultimate stress increases due to both the existence of the replaced sand cushion and the compaction efforts that were adopted to compact the cushion into two layers. The ultimate bearing capacity of footing on stabilized sand cushion without reinforcement is found to be 70 kN/m^2 at S/d=1.00%. It can be concluded that as the subgrade stiffness increases, the bearing capacity increases. The bearing capacity of footing on stabilized sand cushion over soft clay is 2.0 times that of surface footing without stabilization. Moreover, using a single layer of geotextile has good effects, as illustrated in Figure 4. It can also be observed that the ultimate bearing increases with the existence of a single layer of geotextile within the sand cushion at mid-depth. It is also noticed that the footings on reinforced subgrade have higher ultimate loads than in other cases [23, 25]. The existence of reinforcement over the peat layer within the sand cushion can significantly improve and increase the ultimate bearing capacity with less settlement. The ultimate bearing capacity for reinforced cases is found to be 130 kN/m^2 at S/d=0.80%. This increase in the ultimate bearing capacity is backed by the combined effect of both the sand cushion and layer of reinforcement. The ultimate bearing capacity of the reinforced case is found to be 3.71, 1.85 times that of footing on normal ground without stabilization and footing on pure sand cushion without reinforcement, respectively.

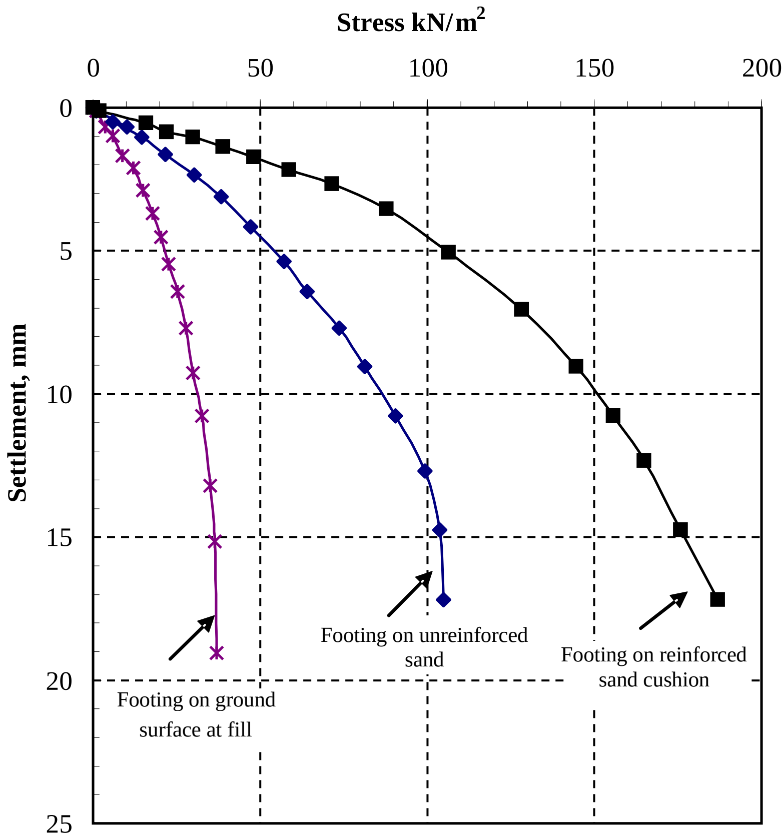

Figure 4. Stress settlement relationship for plate load test at different loading case

The stress carrying by footing over reinforced geotextile layer is higher than the footing without reinforcement; this shows that the geotextile has a substantial effect on increasing the bearing response of the plate load capacity. The footing confirms the better enclosibility of the reinforcement below the plate footing by preventing the sand particles above the geotextile from causing vertical and lateral deformation. Also, the soil between the footing and reinforcement is progressively compacted through the loading stages; as a result, the subgrade soil becomes stiffer and the settlement is reduced. The composite section of sand cushion and reinforcement can also be very significant, particularly when decreasing the transmitted stress to the peat or weak layer.

On the other hand, the use of a geotextile layer as reinforcement can provide an additional improvement where the soil between the plate and the reinforcement is successfully interlocked and acts as a composite rigid section due to the subgrade densification that is achieved. This will decrease the vertical settlement and increase the bearing capacity. It can be seen that a dual effect (the cushion effect and the geotextile effect) was achieved. Thus, the soil over the reinforced layer became stiffer, became one coherent unit, and tended to form a composite stiff section. As a general result, the footing bearing capacity increased and the surface settlement decreased.

The acting stresses above the peat layer for the load condition have been calculated using Boussinesq's method. It is noticed that for normal case footing on ground surface without stabilization, the stress above the peat face is 1 kN/m^2. While this value is found to be 2 and 3.9 kN/m^2 for footing on pure sand cushion and reinforced case, respectively. These theoretical values that were obtained neglect stabilization and reinforcement effects. Therefore, to analyze the effect of the reinforced section in decreasing the stress over the soft pat layer, a numerical analysis should be submitted to verify the reinforcement technique in relieving the stress and describe the improvement mechanism. In addition, the improvement effect of adopting such a sand cushion that is installed in layers and compacted according to specification can be investigated numerically. The effect of repeated load compaction of the equipment used is distinctly explained, and their effect on decreasing the stress over peat is also submitted.

5. Numerical Modeling

In this part of the study, the validation of the numerical study by the field analysis results is introduced. The results gained from the field plate load tests were verified by carrying out numerical analysis using the finite element scheme. The axisymmetric elasto-plastic finite element analysis for circular plate footing was carried out using the commercial program PLAXIS [26]. This numerical analysis aims to identify the behavior of reinforced systems and transmit stress to the peat layer. It also provides information on and clarifies the failure pattern of the studied system. This scheme can be considered a good method for verifying the variables that cannot be obtained in the field.

The soils (sand cushion, medium clay, and peat) in this analysis are modeled by the Mohr-Coulomb failure theory. The main input data or parameters of the Mohr-Coulomb criteria are those that are effortless, slightly friendly, and agree with field testing results. It needs five parameters that are available and easy to obtain from the basic laboratory tests. The axisymmetric model and 6-node triangle elements were adopted for the current analysis. The modulus of elasticity of the different soils at the tested sites was obtained by performing the triaxial tests. The plate of the test setup was a circular one with a diameter 600 mm. It was simulated by a plate element, which is considered very stiff and rough. For the interface element, the interface strength (Rinter) is 0.67, which is appropriate for sand-steel interfaces.

The reinforced element of the adopted reinforcement is modeled as a geotextile element that is mentioned by the axial-horizontal stiffness EA (kN/m) of the geotextile material. In all test series, the length of the reinforced layer is constant, with an adopted length of 4d. The modeled interface with the geotextile element was specified previous to mesh generation. The virtual thickness for positive and negative interface elements is modeled in the plaxis program. Force control performance is considered in all the calculations mentioned in this paper. Where point forces are placed and acted on a geometry point at the center of the plate / footings. Point loads are really line loads in the out-of-plane. The values of point forces are shown in force per unit of length (kN/m).

The properties of the used sand cushion that were simulated in the program input data are ($\gamma = 18.3$ kN/m^3, $\nu = 0.3$, $E = 7500$ kN/m^2, angle of internal friction $= 41^o$, and angle of dilatancy $= 11^o$). The main footing/plate properties are axial stiffness (EA = 24.30 kN/m) and bending stiffness (EI = 171200 $kN/m^2/m$). Where E is the modulus of elasticity of the plate material of the circular footing, A is the cross-section area, and I is the moment of inertia of the cross-section of the footing model.

5.1. Simulation of Dynamic Roller for Compaction

The most important note in this analysis is to consider the repeated load of the roller on the surface of the used sand cushion. The simulation of the installation method of sand cushion in the Plaxis program is significantly considered the compaction repeated load. This can be done to simulate the real behavior of the compaction process in the sand layer (25 cm). It is also considered to be achieved by transmitting stress from compaction to the underlying layer. Numerical modeling of sand cushion and compactor equipment was investigated in the 1950s [27, 28]. The modeling of vibratory rollers and compaction technique is also stated by Yoo & Selig [29]. Therefore, in this study, a finite element model simulating a static compacting roller for the sand layer installed in the field for stabilizing the peat layer was used using PLAXIS 2D 2002, as simulated by Azzam [30]. The soil layer is subjected to dynamic or repeated loading from compaction equipment at the site. A linear-elastic, perfectly plastic model with a Mohr-Coulomb failure criterion is used. First, the model constructed uses an axisymmetric with four sort of triangular elements of 15 nodes for precision. The axisymmetric model is adopted to simulate the strains induced in the direction of the used roller track. The loading scheme used in this study is a uniformly distributed load. This loading technique is applied to the soil through a rigid, weightless plate. The loading is activated and deactivated in the calculation phases in order to simulate the amount of load cycles or passes by a static roller. The simulation of the roller in the plaxis program to achieve the real compaction effort is adopted according to Roudgari [31]. Based on experience, the average value of 0.50 m for the contact width of the roller is considered over the road area to maintain the distribution of the compaction for all layers. The number of cycles adopted in the analysis is 10 cycle for applied load of 25 kN/m^2 within a time interval of 2 seconds and a frequency of 39 Hz. Which means that in simulation there are a total of 20 phases, 10 of which are activated and the other 10 are deactivated for simulated cycles of load. Table 3 shows applicable specifications for simulated drums based on experience and literature [32].

Table 3. Specifications for simulated roller

Parameter	Value
Radius of the drum	0.60 m
Width of the drum	1.68 m
Mass of the drum	1851 kg
Mass moment of inertia of the drum	412 kgm^2
Static axle load	44130 N
Excitation frequency	39 Hz
Amplitude of the oscillating moment	54947 Nm
Suspension drum/frame - stiffness	4×106 N/m
Suspension drum/frame - damping	3×102 N/m
Roller speed	1.11 m/s

The calculation steps involved the following: the first stage of construction, then removing the fill. The second step is placing the sand cushion in layers, and each layer is compacted with a cycle number of 10 with an applied load of 25kN/m^2. The third step is placing the footing and applying the static load until it reaches failure. It can be observed that two load techniques are considered: the first is dynamic load due to compaction, and the second is the normal static load applied to the footing plate. The geometry and dimension of the adopted model are given in Figure 5 for both constriction cases.

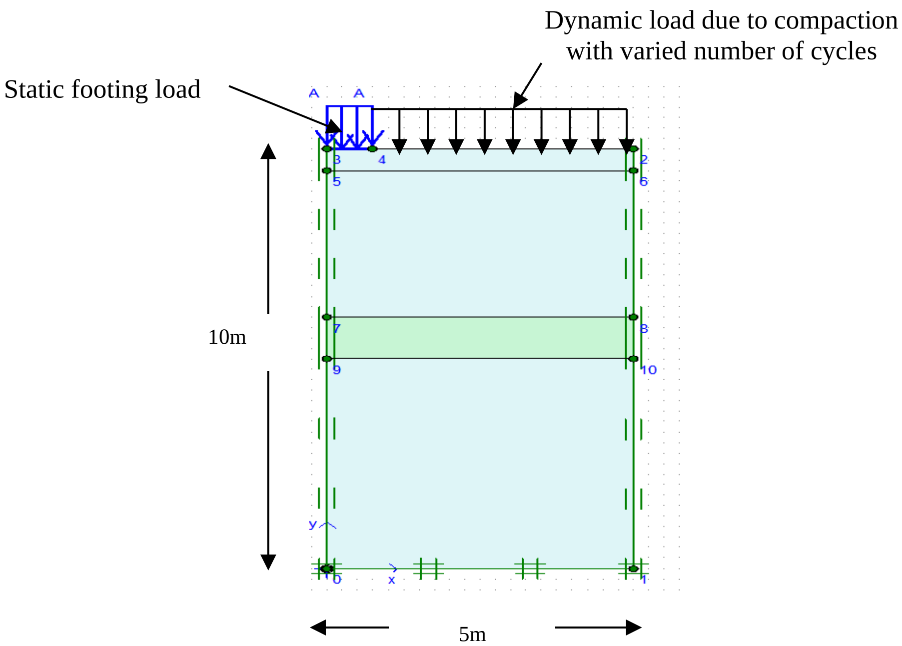

Figure 5. Geometry and dimension of finite element model

5.2. Verification of the Theoretical Analysis Using Field Results

Consider the dynamic response mentioned above; a contrast between the stress settlement responses is obtained using the finite element analysis. The field results that were recorded from the relevant plate load tests for the three cases mentioned in Figure 3 were run with a numerical program. The numerical results of the tested three cases are compared with those obtained in the field and plotted in Figure 6. The finite element results are reasonably accurate for computed values of the ultimate bearing capacity. The numerical results are close to those of field consequences and have the same trends. The results of the numerical study confirm the field value and justify the effectiveness of the dynamic condition applied to the replaced sand cushion. However, a little difference between the results from the numerical analysis and those obtained from the field test is observed. This variation is due to environmental conditions in the field and the accuracy of the input data.

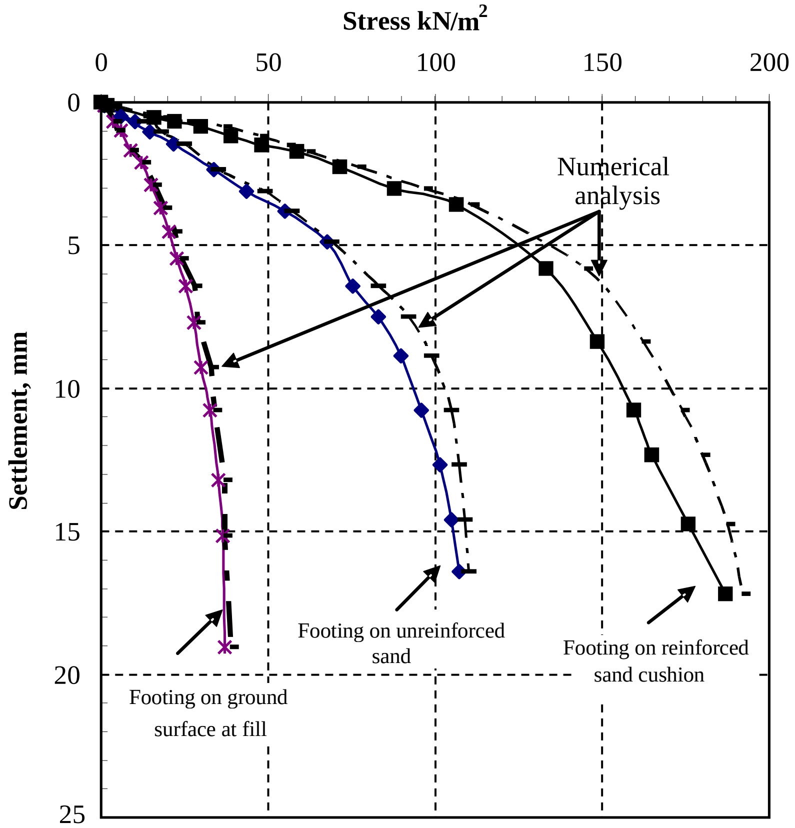

Figure 6. Comparison of stress settlement curves for field test data test and numerical results for different cases

5.3. Numerical Outcomes

The main aims of the finite element study are to verify the field test results and shed light on the parameters that cannot be measured in the field. It also tries to clarify the effectiveness of the adopted dynamic response on the improvement of the underlying soil and relieve the stresses transmitted to the weak peat layer. Therefore, the effect of variation in the number of cycles and applied load is examined to reach an acceptable degree of improvement in controlling the stress and settlement of the peat layer. The studied series using numerical modeling is shown in Table 4, considering the thickness of the sand cushion with or without reinforcement, applied dynamic stress, and number of cycles to repeat the load. These series try to determine and evaluate the effect of dynamic acting repeated stress at the surface of the installed sand cushion on the footing ultimate bearing capacity and transmitted stress to the peat layer. Due to the limited space, some of the studied series for the stress settlement curves for plat/e footing on sand cushions with different thicknesses in the case of sand without/with reinforcement are presented in Figure 7 for the condition of N =10 cycles and a dynamic stress of 25 kPa. This figure confirms that the thickness of the sand cushion has a good effect on modifying stress settlement curves (Figure 7-a) in the case of pure sand cushion without reinforcement. As the sand thickness increased, the ultimate bearing capacity increased with less settlement. The installation of sand cushions with adequate depth can significantly produce stiff subgrade that reduces the transmitted stress to underlaying strata with minor settlement. It also modifies the bearing capacity failure from general shear failure to punching shear failure with limited stress. While the existence of reinforced elements within the subgrade sand cushion with a dynamic process can effectively induce a combined effect in improving the load-carrying capacity with obvious values, as confirmed by Figure 7-b. These figures demonstrated that the ultimate bearing capacity improved well with the increase of sand cushion when a reinforced layer was used.

Table 4. Studied series for numerical analysis

Series	Constant parameters	Variable parameters	
1	H/D = 0.5, ϕ = 41°, Number of cycle N = 10 H/D = 1.0, ϕ = 41°, Number of cycle N = 10 H/D = 1.5, ϕ = 41°, Number of cycle N = 10	Sand cushion without reinforcement	Applied dynamic stress σ = 25, 30, 40 kN/m^2
2	H/D = 0.5, ϕ = 41°, Number of cycle N = 10 H/D = 1.0, ϕ = 41°, Number of cycle N = 10 H/D = 1.5, ϕ = 41°, Number of cycle N = 10	Sand cushion with reinforcement, single layer at mid depth	Applied dynamic stress σ = 25, 30, 40 kN/m^2
3	H/D = 0.5, ϕ = 41°, σ = 25 kN/m^2 H/D = 1.0, ϕ = 41°, σ = 30 kN/m^2	Sand cushion without reinforcement	Number of cycle N = 10. 15, 20
4	H/D = 0.5, ϕ = 41°, σ = 25 kN/m^2 H/D = 1.0, ϕ = 41°, σ = 30 kN/m^2 H/D = 1.0, ϕ = 41°, σ = 30 kN/m^2	Sand cushion with reinforcement, single layer at mid depth	Number of cycle N = 10. 15, 20

For all studied series, frequency equal 39 Hz is considered. The length of reinforced layer is constant with length of 4d.

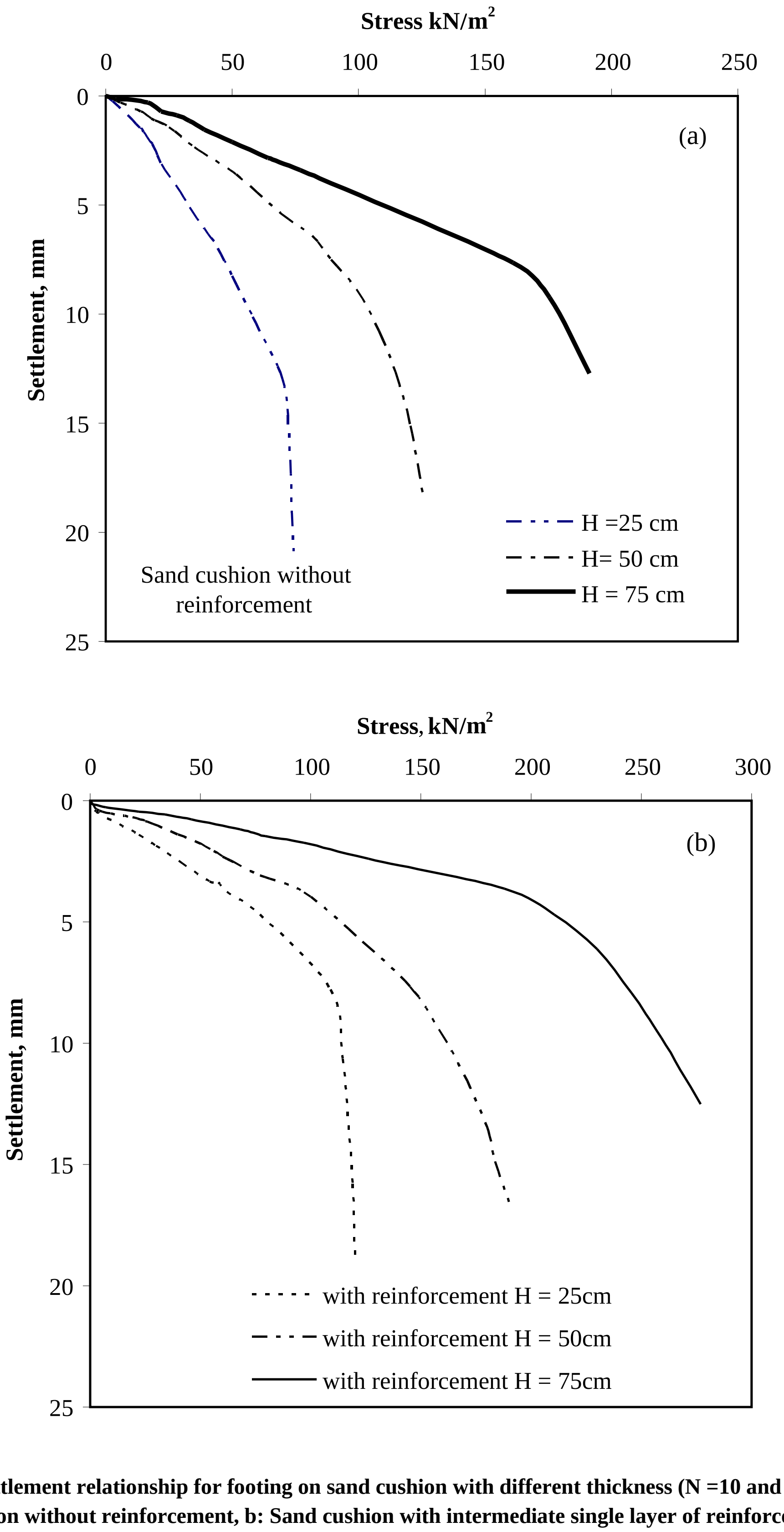

Figure 7. Stress settlement relationship for footing on sand cushion with different thickness (N =10 and σ= 25kPa), a: sand cushion without reinforcement, b: Sand cushion with intermediate single layer of reinforcement

The major cause of this occurrence of subgrade improvement is the existence of a reinforced layer within the sand cushions that distinctly produced a stiff composite slab. This slab is more effective in redistributing the stress to the deep layer with minor values. It can be seen that the partial substitute of the soil with the reinforced sand cushion layer results in a redistribution of the stresses to a wider region, consequently eliminating the stress focus and producing an enhanced distribution of the obtained stress. That's why the ultimate bearing capacity can be enhanced while the plate footing settlement is controlled. It is noticed that the stress-settlement curve is curved in shape, tends to be steeper, and takes on an approximately linear form before attaining failure. A peak stress is not considered, and no definite failure point is recognized (Figure 7-a) [33]. The failure mode can be diverted to punching shear failure due to the reinforced effect.

On the other hand, for a deep analysis of such a phenomenon, Figure 8 shows the relationship between the ultimate bearing capacity of plate footing and sand cushion thickness in the form of a ratio (H/D) for both sand cushions with/without reinforcement at different dynamic stresses. It can be seen that for a normal sand cushion without reinforcement, the increase in thickness H increases the ultimate bearing capacity with upper increase in acting dynamic stress. The bearing capacity is in good relation to H/D [34, 35]. It is noticed that for sand cushion without reinforcement, the variation of ratio H/D from 0.5 to 1.50 (Figure 8-a) has a substantial effect on increasing the ultimate bearing capacity, as it increased from 43 to about 98 kPa (i.e., an increase of about 227%) for an applied dynamic load of 25 ka.

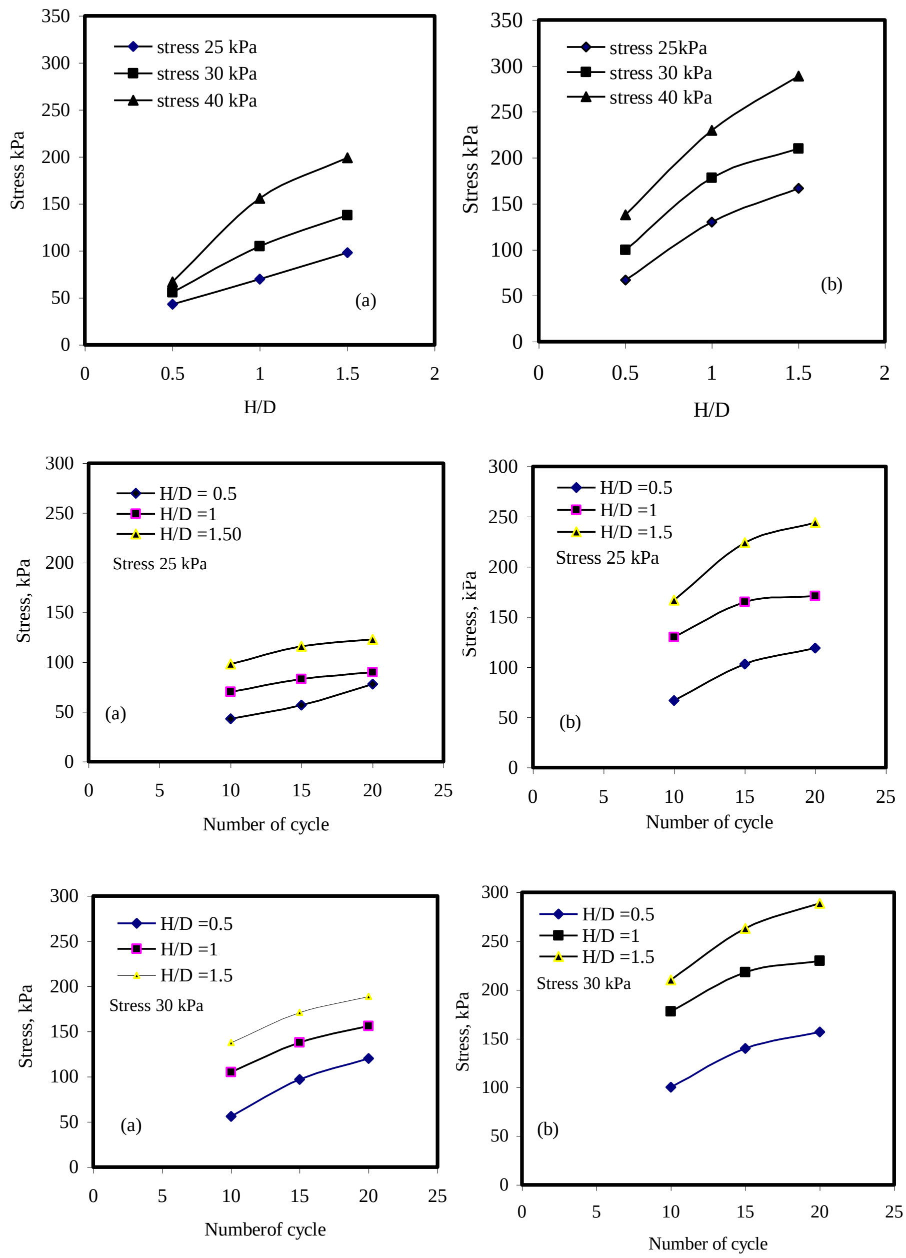

Figure 8. Variation of ultimate bearing capacity- for footing on sand cushion with different thickness at different dynamic stress, a: Sand cushion without reinforcement, b: Sand cushion with intermediate single layer of reinforcement

These values are found to be 246, 297% for applied stress of 30 and 40 kPa, respectively. It is clearly shown that the layer of sand cushion helps to increase the ultimate bearing capacity of the footing because the adopted cushion is stiffer and stronger than the natural clay. Moreover, as the sand cushion depth is increased, this means that the number of layers is also increased, therefore the gradual compaction efforts are increased, and as a result, the under-laying layer is increased. The compacted sand cushion with higher stress values can be considered a stiff subgrade coherent mass that provided a higher bearing capacity.

On the other hand, the effect of using a single layer of reinforcement in the form of geotextile within the sand cushion at mid-depth can also have a great effect with applied compaction efforts (Figure 8-b). It is also found that the combined effect of both the existence of reinforcement and dynamic load is achieved, and the degree of the improvement in the ultimate bearing capacity is attributed. It can be confirmed by the relevant Figure 8-a, which describes the effectiveness of such a reinforced layer compared with cases of normal sand cushion. It has been found that at the same lower value of H/D = 0.5, the ultimate bearing capacity of reinforced sand cushion is found to be greater than that of the normal case without reinforcement by as much as 1.55, 1.78, and 2.05 times for applied stress of 25, 30, and 40 kPa, respectively. While at H/D = 1.50, these ratios are reached at 1.70, 1.52, and 1.45 times the ultimate bearing capacity of the sand cushion without reinforcement in the same order of applied stress. It can be concluded that using a single layer of reinforcement can effectively increase the ultimate bearing capacity instead of increasing the cushion depth with effective applied stress, as confirmed by Figures 8-a and 8-b.

Moreover, the effect of the number of load cycles on the ultimate bearing capacity of sand cushion without/ with reinforcement is suited at different cushion depths and applied loads of 25 and 30, as shown in Figures 9-a to 9-d. In general, it can be seen that an increase in the number of load cycles can distinctly increase the ultimate bearing until reaching the optimum number of cycles. It is noticed that increasing the load cycle from 10 to 20 can effectively increase the ultimate bearing capacity with an obvious amount for normal and reinforced sand cushions under an applied load of 25 kPa.

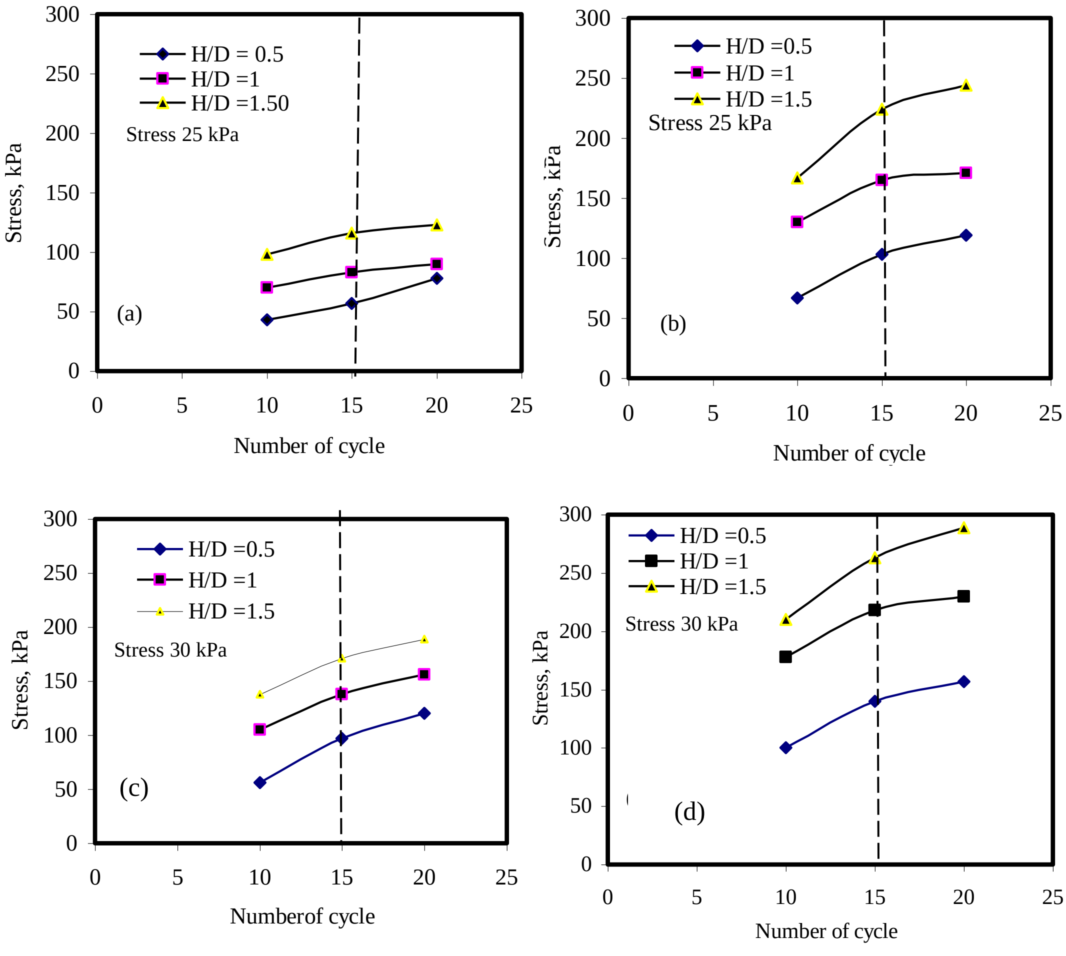

Figure 9. Variation of ultimate bearing capacity for footing on sand cushion with different thickness at different dynamic stress, a: Sand cushion without reinforcement with stress 25kPa, b: Sand cushion with intermediate single layer of reinforcement with stress 25kPa, c: Sand cushion without reinforcement with stress 25kPa, d: Sand cushion with intermediate single layer of reinforcement with stress 25kPa.

The increase in ultimate bearing capacity is found to be 1.46, 1.28, and 1.25 times the initial value at N = 10 for non-reinforced sand cushion (Figure 9-a) with a ratio of H/D = 0.5, 1, and 2, respectively. While for the reinforced case their beneficial effect with increase of load cycle in the same trend (Figure 9-b), these values are extracted to be (1.77, 1.43, and 1.42) times of the initial values of N = 10 and correspond to the sand cushion depth ratio of (H/D = 0.5, 1 and 2), respectively. Whereas, varying the load number of cycles from 10 to 20 for an applied stress of 30 kPa can also increase the ultimate bearing capacity by as much as 2.14, 1.48, and 1.36 times the initial value of the unreinforced sand cushion in the case of H/D = 0.5, 1, and 2, respectively. However, for that order, the degree of improvement in the ultimate bearing capacity in the reinforced case is estimated to be 1.57, 1.29, and 1.37 times the system at a load cycle of 10. It can be observed that a lesser variation is achieved when the load cycle is reached at 15. Over this range, the increase in the ultimate load capacity is nearly insignificant for all investigated cases. It may be said that the optimum number of cycles to be adopted is 15. Any additional increase does not have any noteworthy effect on the footing response, but a minor variation is obtained. The most effective parameter is the applied load for compaction effort and the thickness of the sand cushion.

5.4. Prediction Procedure to Assessment the Dynamic Response of Compaction

In general, an extensive cycle of rollers has two major impacts on the surrounding soil. Firstly, reduce the expected settlement by densifying the soil. Secondly, increase the bearing capacity of the bearing soil [30]. Consequently, the major aim of using a sand cushion or geotextile layer is to provide a stiff layer to relieve the increase in vertical stress over the weak layer. So, there is a need to predict the required thickness of sand cushion or use the geotextile layer to achieve the design requirement.

Based on the above-mentioned parametric study and previous studies, the steps for predicting the preliminary thickness of the sand cushion are as follows: (1) predict the vertical and ultimate bearing capacity of using a finite element using the available data from the soil profile; (2) use the available data to simulate the dynamic response of a roller with a number of cycles not less than 10 cycles and a frequency not less than 30 Hz and an applied stress of 25 kPa by calculating the final settlement and ultimate bearing capacity corresponding to different sand cushion thicknesses; (3) estimate the optimum thickness according to the design criteria of the project, such as a as a road, rail way, building, etc.

6. Conclusions

Based on the field data and numerical simulation for the field test and the parametric study, the following observations were made:

- The results showed that using a geotextile layer as a reinforcement layer reduced the final settlement and distributed the concentrated stress over a large area.
- The results showed that the composite compacted cushion with both a higher number of passes and stress has a great effect on relieving the stresses transmitted to the face of the peat layer with lesser deformation.
- The results showed that the increase in the number of load cycles has a significant effect on the ultimate bearing, where the cycle pass rate value is 10 to 20, with an average value of 15 cycles.

7. Declarations

7.1. Author Contributions

Conceptualization, A.B., W.A., and M.E.; methodology, A.B., W.A., and M.E.; formal analysis, A.B. and W.A.; investigation, X.X.; resources, A.B. and M.E.; writing—original draft preparation, A.B., W.A., and M.E.; writing—review and editing, A.B., W.A., and M.E. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

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

7.3. Funding

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

7.4. Conflicts of Interest

The authors declare no conflict of interest.

7.5. Competing Interests

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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