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수직방향으로 보강된 사질토층의 지지력에 관한 연구

Bearing Capacity of Vertically Reinforced Sand Subgrades

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Abstract

This paper presents a new method of soil improvement by using semi-flexible vertical reinforcing elements which shows promise for future work. Load tests were conducted on two model footings in a sand box using unreinforced sand and also by reinforcing the sand with vertical reinforcing elements. The ultimate bearing capacity for the unreinforced and reinforced sand has been compared. The effect of length, spacing, lateral extent of the reinforcement, and the initial relative density of sand in increasing the ultimate bearing capacity have been evaluated. The effect of roughness of the reinforcing elements has also been investigated. Based on the results of these model footing tests, it appears that significant improvement in the ultimate bearing capacity of loose and medium sands can be achieved by reinforcing with vertical elements.

요 지

본 논문은 준강성 보강재를 수직방향으로 설치함으로써 연약지반을 개량할 수 있는 장래 현장에서 유용하게 사용될 보강토방법을 제시하였다. 실내모형실험은 보강재를 연약한 사질토층에 수직방향으로 설치하고 그 상부에 두 종류의 모형얕은기초를 축조한 후 보강되지 않은 사질토층과 보강된 사질토층에 대한 지지력을 비교하였다. 또한 보강재표면의 거칠기에 따른 효과와 보강재의 길이, 설치간격, 측면보강범위와 사질토의 초기상대밀도에 따른 극한지지력의 증가에 대하여 평가하였다. 실험결과 상대밀도가 낮거나 중간 정도인 사질토층에 보강재를 수직방향으로 설치하였을 때 극한지지력이 상당량 증가됨을 알 수 있었다.

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1. Introduction

The concept of improving weak and difficult subsoils for safe and economical construction has been in use for more than a century. However the techniques of soil improvement have been changing and during the last three decades, the concept of soil improvement by reinforcing it with tension-resistant elements in the form of sheets, strips, metal nets, woven or resin fibers, polymers and plastics has received the attention of researchers and field engineers alike. The applications of reinforced earth technology to date show that most of the work has been done with reinforcement laid-horizontally several studies relating to the evaluation of bearing capacity of shallow foundations supported on soil with horizontal layers of reinforcement have been published.

Binquet and Lee[1] conducted model footing tests on reinforced earth slabs and studied the effect of the number of layers of horizontal reinforcement, the spacing between the reinforcement layers, and the distance of the first layer of reinforcement measured from the bottom of the foundation. Marked improvement in bearing capacity was observed as a result of soil reinforcement. They also investigated the failure mechanism of horizontally reinforced soils. Akinmusuru and Akinbolade[2] investigated the effect of flat strips of rope fiber embedded horizontally in granular soil on the bearing capacity of square footing. The effect of horizontal spacing of the fiber strips, vertical spacing between the layers of reinforcement, number of layers, and the depth below the footing to the first layer of reinforcement were investigated. They observed that the bearing capacity increased with the number of layers of reinforcement below the footing. The optimum results were obtained with three layers of reinforcement when the horizontal spacing of fibers in the layers was 0.5B (B=width of the footing) and the vertical distance between the layers was 0.5B.

Fragaszy and Lawton[3] studied the effect of soil density and length of reinforcing strips on the improvement of bearing capacity of horizontally reinforced sand subgrades. Guido *et al.*,[5] and Kinney[6] studied the beneficial effects of geotextiles placed at the interface of a finely crushed gravel underlain by a soft clay by conducting model tests on circular footings subjected to sinusoidal loads. Ingold and Miller[7] evaluated the behavior of a footing supported by a clay soil with horizontal geogrid reinforcement. Milligan and Love[8] made a study of the behavior of a strip footing on an aggregate layer overlying soft ground with horizontal geogrid reinforcement.

Bassett ans Last[9] stuided the possibility of using non-horizontal reinforcements in soil under the foundation. Gray and Al-Refeai[10] evaluated the strengthening effects of randomly-distributed discrete fibers mixed with sand.

Hence it appears possible to use semi-flexible non-horizontal reinforcement in soil to improve its load-bearing capacity for supporting shallow foundations. Vertical reinforcement may be easier to install than the horizontal reinforcement since no soil excavation or recompaction may be needed. A preliminary study for determination of the beneficial effects of vertical reinforcement on the load-bearing capacity of a model footing resting on the surface of a sand layer reinforced with vertical semi-flexible reinforcement (i.e., metal rods) has been reported by Verma and Char.[11] Field applications of vertical reinforcement by utilizing sand drains and sand compaction piles for large-scale land reclamation projects have been reported by Arai[12] and Shin *et al.*[13]

The present study is related to the evaluation of the beneficial effects of vertical reinforcement in sand relating to the bearing capacity of shallow strip foundations. A laboratory investigation was conducted to study the important parameters influencing the effectiveness of the vertical reinforcement in improving the load-settlement characteristics of sand subgrades by conducting a series of model footing tests. The details of these tests and the results obtained during this study are presented below.

2. Model Test Details

2.1 Test Set-Up

Model footing tests under plane strain conditions were conducted in a sand box measuring 914.4 mm×152.4 mm×609.6 mm (length×width×height). The longer side of the box was made of thick plexiglas to observe the deposition of sand in the box during sample preparation and to observe the development of the failure surface in the sand under the foundation during the model tests. The smooth surface of the plexiglas also helped

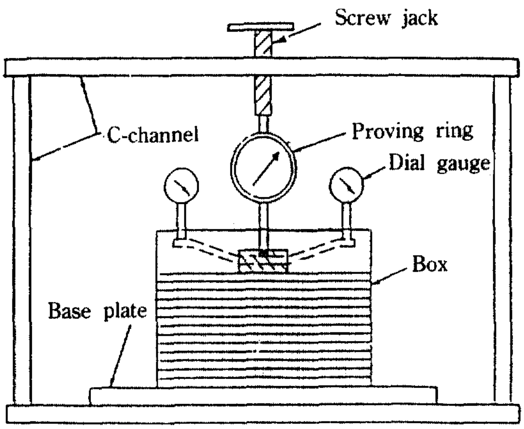

Fig. 1. Laboratory test set-up

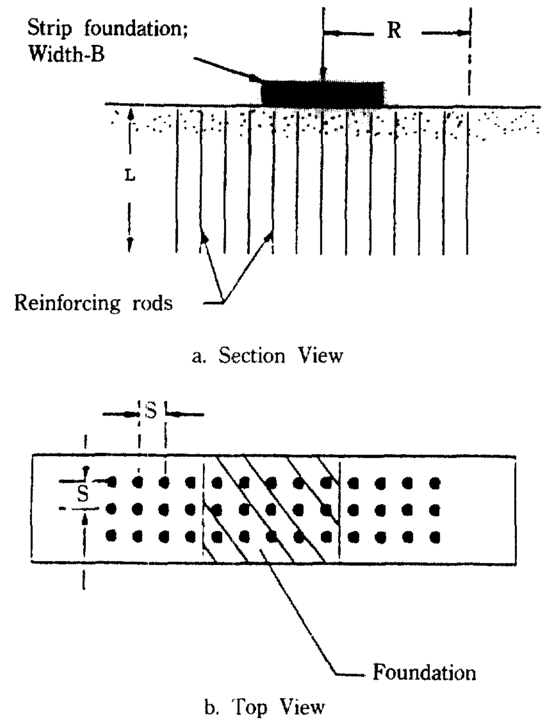

Fig. 2. Geometry of reinforcement in the soil box

to minimize the effects of side resistance on the rupture surface in the soil. Because the interface friction angle between plexiglas and sand is too small to influence the test result. The walls of the box were also reinforced against lateral deformation by stiffening them with angle irons. A schematic diagram of the test arrangement is shown in Fig. 1.

The load on the model footing was applied with the help of a hand-operated screw jack and measured with a proving ring. The vertical settlement of the footing was observed with a pair of dial gauge fixed to extension links on either side of the model footing.

2.2 Test Parameters

The model footing used in this study measured 50.8 mm (width)×139.7 mm×50.8 mm (thickness) and 101.6 mm (width)×139.7 mm×50.8 mm (thickness) and were cut from hard wood. The base of the footing was made rough by gluing sandpaper to the base.

The soil used for this study was medium silica sand with a Unified soil classification of SP. The effective size of the sand and the uniformity coefficient were 0.398 mm and 1.2, respectively. The tests were conducted by depositing sand at initial relative densities of 45, 60, and 70 percent.

Two types of reinforcing elements were used in this investigation: (a) plain reinforcement that consisted of 1.58 mm diameter steel rods and (b) rough (or ribbed) reinforcement which consisted of 1.58mm diameter steel rods with a single grain layer of very fine sand bonded on to its surface using an epoxy glue. Several combination of length (L), spacing (S), and extent of the reinforcement (R) were used during the tests. These combinations are listed in Table 1 which also summarizes the other test parameters. The parameters L, S, and R are defined in Fig. 2a, b.

2.3 Test Producedure

The sand test beds were prepared by depositing sand in layers through a long-stemmed funnel. The height of free fall of sand to ensure a deposit of uniform density was decided by conducting trial tests. This technique made possible to form a relatively lower density of sand layer. The uniformity of layers was also checked by placing small containers before depositing the particular layer and taking out and weighting these samples after the layer was deposited.

The installation of vertical reinforcement was

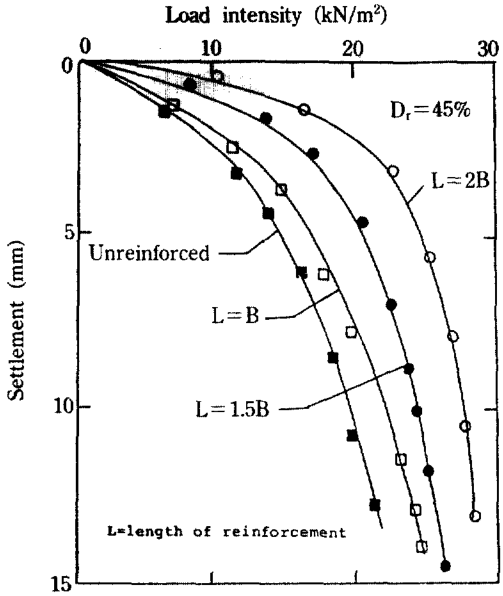

Fig. 3. Settlement vs. load intensity plot for footing with B=50.8 mm, R=B, and S/B=0.4

followed the construction procedure of pile foundation in field, that is, after proper preparation of the sand bed, the vertical reinforcement was pushed into it at predetermined spacings. The sand bed was again leveled at the end of placement of the reinforcement and before placing the model footing on it.

The load to the foundation was applied in increments. Each load was maintained at a constant value until the movement of the footing stopped. The process of loading was continued until the ultimate load was reached or the settlment became excessive.

3. Model Test Results and Discussion

The general effect of providing vertical reinforcement in the soil was to increase its ultimate bearing capacity compared to the case where no reinforcement was provided. Fig. 3 shows typical plots of load intensity versus settlement for the footing having a width of 50.88 mm for both the unreinforced and reinforced sand with L=B, 1.5B and 2B, and S/B=0.4. These plots are for sand at an initial relative density of 45%. It can be seen from these plots that, with the introduction of reinforcement, the ultimate bearing capacity increase and the load intensity for any given value of settlement is higher for a reinforced soil than for an unreinforced soil. The improvement in the load-settlement characteristics of the soil reinforced with vertical elements may be due to several factors, such as increase in density of sand (due to installation of reinforcing elements), the change in stress distribution within the soil, and the change in the mode of failure. The stress distribution on the improved ground was assumed as an uniform load even if it was more concentrated on the reinforced rod.[14]

Three different failure modes were observed, general shear failure(complete collapsed), partially collapsed, and local shear failure. The general shear failure mode was observed for the case of Dr=45%, L=B and R=B, this failure mode was somewhat like bulging failure due to lack of confinement.

The intermediate failure mode, partially collapsed failure mode, was observed for the case of Dr=45%, L=1.5B, R=2B and Dr=60%, L=B, R=B. The local shear failure mode was observed for the case of Dr=60%, L=2B, R=2B and Dr=70%, L=1.5B, 2B and R=2B with reinforcement spacing of 0.2B.

Thus, the failure mode of reinfored ground was dependent on relative density of sand, Dr, and reinforcing parameters, L, S and R (Table 1). The effect of reinforcement parameters such as Length (L), spacing (S), and extent (R) was first investigated and an optimum combination of these parameters was determinved. The effects of initial soil density and roughness of reinforcement were then determined.

3.1 Effect of the length of reinforcement (L)

Typical plots showing the length of reinforcing elements on the load settlement characteristics of the footing with the width B=50.8mm tested on a sand bed at an initial relative density of 45% have been shown in Fig. 3. In these tests the spacing (S) and extend of reinforcement (R) were maintained constant at 0.4 B and B, respectively, and the tests were conducted by using reinforcing

Table 1. Test Parameters

Parameters	Range	
Footing size (mm)	50.8×152.4	101.6×152.4
Initial relative density, Dr(%)	45, 60, 70	45, 60, 70
Length of reinforcement, L	B, 1.5B, 2B	B, 1.5B, 2B
Spacing of reinforcement, S	0.2B, 0.3B, 0.4B	0.1B, 0.15B, 0.2B
Extent of reinforcement, R	B, 2B	B, 2B

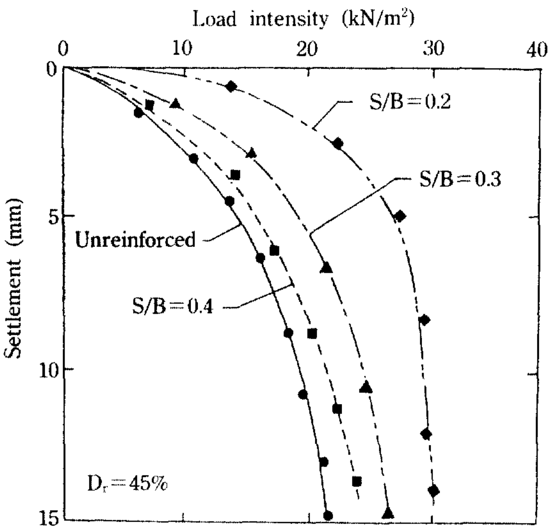

Fig. 4. Settlement vs. load intensity plot for footing with B=50.8 mm, R=B, and L=B

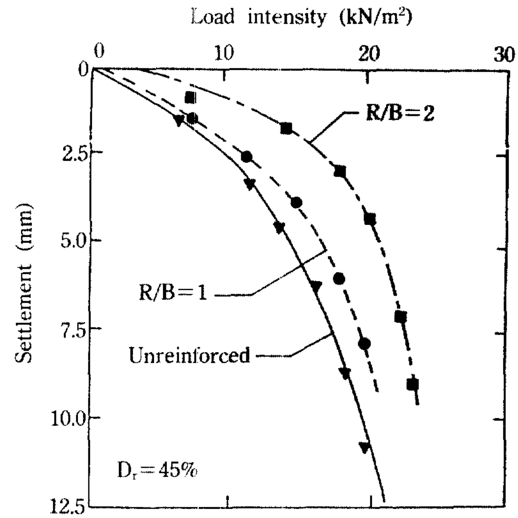

Fig. 5. Settlement vs. load intensity plot for footing with B=50.8 mm, R=B, and S/B=0.4

elements of length, L=B, 1.5B and 2B. As can be seen from this figure, both the ultimate bearing capacity and the load-settlement characteristics improve with increase in length of reinforcing elements. Similar effects of length reinforcing elements on bearing capacity were observed in all other tests.

3.2 Effect of spacing on reinforcement (S)

Typical plots showing the effect of spacing on vertical reinforcing elements on the bearing capacity and load-settlement characteristics of the footing with B=50.8 mm are shown in Fig. 4. For these tests, the length of reinforcement (L) and its extent (R) were maintained constant and spacing S=0.2B, 0.3B, and 0.4B were used. It may be observed from Fig. 4 that the ultimate bearing capacity and the soil pressure for a given value of settlement increase as the spacing of reinforcing elements is decreased. The results of other tests conducted for investigating the effect of spacing also gave similar results.

3.3 Effect of extent (R)

A typical plots showing the effect of the extent of reinforcing (R) is shown Fig. 5. The general effect of increasing the extent from R=B to R=2 B is to increase the ultimate bearing capacity (with parameters L and S kept constant).

3.3.1 Optimum Combination of Length, Spacing, and Extent of Reinforcement.

Based upon the results of load tests conducted on footings with B=50.8 mm and 101.6 mm and within the range of variables L, R, and S, used in this study, it was observed that the best improvement in ultimate bearing capacity of the combi-

Table 2. Optimum Combination of Reinforcement Parameters

	Values for best results	
	Footing width, B (mm)	
Reinforcement parameter	50.8	101.6
Length, L	2B	2B
Spacing S	0.2B	0.15B
Extent, R	2B	2B

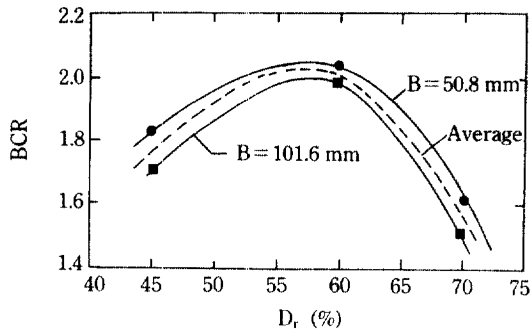

Fig. 6. Plot of BCR vs. D_r for optimum combination of reinforcement parameters

nation of reinforcement parameters would be as shown in Table 2 for any given initial relative density of sand. Spacing of vertical reinforcement for best results (i.e., maximum imprvement in this case) is in the range of 0.15B to 0.2B.

In order to make a quantitative assessment of the beneficial effects of vertical reinforcing elements in improving the ultimate bearing capacity of the reinforced soil compared to the unreinforced soil at different placement density of sand, a non-dimentional term, bearing capacity ratio (BCR), can be defined as

$$BCR=\frac{q_u(r)}{q_u(u)} \tag{1}$$

in which $q_u(u)$=ultimate bearing capacity of unreinforced soil and $q_u(r)$=ultomate bearing capacity of reinforced soil.

Plots were then made of the BCR versus Dr (initial relative density of sand) for footings with B=50.8 mm and 101.6 mm at optimum combinations of reinforcement parameters as shown in Table 2. It can be observed from Fig. 6 that the value of BCR for all initial relative densities of soil used in the tests is greater than one. The beneficial effects of the vertical reinforcement therefore occur at all placement densities used in this study. The magnitude of the increase in BCR is a function of the initial relative density of sand. The value of BCR is seen to increase with the increase of Dr up to a maximum value and decreases thereafter (Fig. 6). This may be due to the fact that when the vertical reinforcements are installed in the sand at relatively lower densities, it becomes compacted and the combined effect of this increase in density and the presence of reinforcing elements results in a substantial increase in the value of the BCR. When the reinforcements are installed in a relatively dense sand, the upper sand layers get somewhat loosened and the increase in BCR diminishes. The maximum value of BCR will thus be achieved at some intermediate density. For the present tests, the maximum value was observed at a relative density of compaction of about 60%. It is also seen from Fig. 6 that the plots of BCR vs. D_r are rather close and may be represented by an average curve and are thus independent of the width of the foundation.

From Figs. 3, 4, and 5, the magnitude of foundation settlement without reinforcment is much larger than foundation settlement with reinforcement to yield the ultimate bearing capacity. The result of the present tests indicate that the use of vertical reinforcement in sand subgrades helps improve thier bearing capacity performance and reduce the settlement significantly.

3.4 Effect of Roughness of Reinforcement

The tests conducted by using rough (ribbed) reinforcement showed that rough reinforcing elements are more effective in improving the load settlement behavior of sand as compared to the case of plain reinforcement. Fig. 7 shows typical pressure versus settlement plots for the footing with B=101.6 mm for sand reinforced with plain and ribbed reinforcement at an initial relative de-

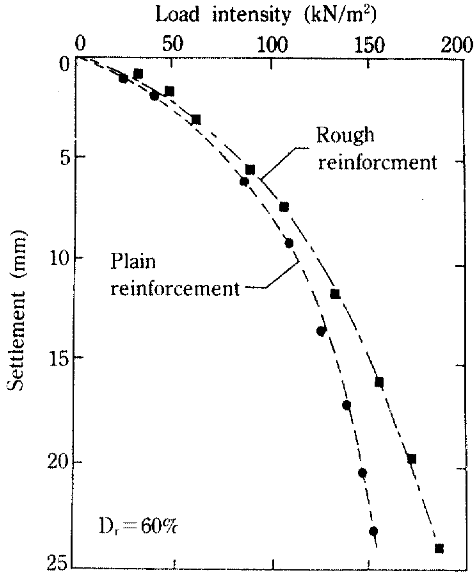

Fig. 7. Plot of settement vs. load intensity for footing with B=101.6 mm, L/B=1.5, R/B=2, and S/B=0.2

nsity of 60%, L=1.5B, R=2B, and S=0.4B. Benefits of using ribbed reinforcement as compared to plain reinforcement are obvious from these plots (Fig. 7). A similar trend was obvious in all tests where rough reinforcement was used. Other parameters remaining constant, the ultimate bearing capacity was generally 40~50% higher with ribbed reinforcement as compared to the value for the case of plain reinforcement. It must be mentioned here that, even though rough reinforcement is more effective in improving the load settlement behavior of sand deposits compared to plain reinforcement, its installation shows some problems.

It is true that the diameter of rough reinforcement is somewhat larger than that of plain reinforcement due to the fire sand coating. The amount of this coating volume could increase the overall relative density of sand layer, also it creates disturbance of surrounding soil during the process of driving. But overall benefits of using rough reinforcement shown in Fig. 7 could be cased by the increment of interface friction angle, roughend surface-sand.

The interface friction angle (δ) of sand-rough surface was the same degree as the soil friction angle ϕ ($\delta=\phi$). However, the interface friction angle (δ) of sand-smooth surface was approximately, 2/3 of internal soil friction angle ($\delta=2/3\phi$).

4. Conclusions

The beneficial effects of using vertical reinforcing elements in improving the load settlement behavior of sand subgrades have been demonstrated through a series of model footing tests conducted in the laboratory. The improvement in the ultimate bearing capacity of reinforced sand subgrades depends upon the spacing, length, and extent of the reinforcing elements. Based on the model footings and soil densities used in these tests, the best results can be obtained by using the reinforcing elements as suggested below:

1. Spacing of the reinforcement used should be about 0.15 to 0.2 times the width of the footing.
2. The length of the reinforcment used should be at least equal to the width of the footing and preferably should be 1.5 times the footing width since placement of L > about 1.5 would be difficult.
3. The extent of the reinforcement used should be at least 1 to 1.5B.

The rough reinforcement was found more effective in improving the ultimate bearing capacity as compared to plain reinforcement.

For the sand used in this study, the beneficial effects of using vertical reinforcement are more prominent for soils at lower initial densities. The bearing capacity ratio increases as the initial density of sand increase, becomes maximum at a certain optimum density, and decreases thereafter. Further studies are necessary to quantify parameters for actual design conditions.

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