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Geogrid로 보강된 사질토층에 얕은 기초의 동적 하중-침하 관계에 관한 연구

Dynamic Load-Permanent Settlement of Shallow Foundations Supported by Geogrid-Reinforced Sand

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Abstract

This paper has primarily been directed to evaluate the beneficial effects of geogrid reinforcement in a medium sand on the ultimate bearing capacity (UBC) of a surface foundation. Also, this study was conducted to investigate the permanent settlement of a shallow square foundation in improving the cyclic load-settlement characteristics of reinforced sand deposits by conducting a series of laboratory model tests. Use of geogrids provides an economical and time efficient method for improving load-settlement and strength characteristics of weak soils. Especially the geogrid reinforced soil will be necessary in the case of foundation supporting machines, embankments for railroads, and foundations of structures in earthquake-prone areas. Finally, the test results indicate that the use of geogrid reinforcement in sand subgrades improves their performance under dynamic loads which shows promise for future work.

요 지

본 논문은 중간 정도의 밀도를 가진 사질토층에 있어서 얕은 기초의 극한 지지력에 대한 Geogrid 보강의 긍정적인 효과를 우선적으로 평가하고자 하였다. 보강된 사질토층의 정적, 반복 하중에 따른 침하 특성을 개선함에 있어 일련의 실내 모형 시험을 수행하므로써 얕은 정방형 기초의 극한, 허용 지지력을 연구하고자 하였다. Geogrid의 사용은 연약 지반의 강도 특성 및 하중-침하 관계에서의 개선을 위한 경제적이면서도 시간 절약의 효과를 가져올 수 있다. 특히 Geogrid로 보강된 지반은 기계 기초,

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철로 제방, 그리고 지진 예상 지역의 구조물 기초 등에 필수적이다. 결론적으로 본 실험 연구의 결과는 사질토층에 Geogrid로 보강을 실시하므로써 정, 동적 하중에 대한 지반의 특성이 개선됨을 보여주고 있었으며, 향후 현장에서 유용하게 사용될 새로운 보강토 방법을 제시하였다.

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1. Introduction

During the last twenty years or so, several techniques have been developed to improve the load bearing capacity of soil supporting a foundation. Fig. 1 shows a schematic diagram of a square shallow foundation supported by a layer of geogrid-reinforced sand (B=width of foundation, u=distance of the first layer of reinforcement from the bottom of the foundation, d=depth of geogrid reinforcement, N=number of geogrid reinforcement layers, and b=width of geogrid reinforcement).

Several laboratory model test results are presently available which relate to the determination of permanent settlement of shallow foundation subjected to various types of dynamic loading. Cunny *et al.*,[2] Shenkman *et al.*,[6] Jackson *et al.*,[4] conducted several small-scale laboratory tests to observe the load-settlement relationships for shallow foundations supported by unreinforced sand and clayey soils due to vertical transient loading. The most results of these tests have been summarized by Das.[3] The transient loads to which the footings were subjected were of nature shown in Fig. 2. The nature of settlement of footing with time during the application of the dynamic load is also shown in the same figure. In general, during the rise time (t_r) of the dynamic load, the settlement of a footing increases rapidly. Once the peck load [$Q_{d(max)}$] is reached, the rate of settlement with time decreases. However, the total settlement of a footing continues to increase during the dwell time of the load (t_{dw}) and reaches a maximum value (s_{max}) at the end of dwell time. During the decay period of the load (t_{de}), the footing rebounds to some degree. Raymond *et al.*[5] have presented the results of the cyclic load amplitude and the related settlement of strip surface foundations supported by dense sand. For these study, the cyclic loadings approximated a rectangular wave form with a frequency of 1 cycle/sec. The model foundation was thus subjected to various magnitudes of cyclic load (σ_d/q_u=13.5% to

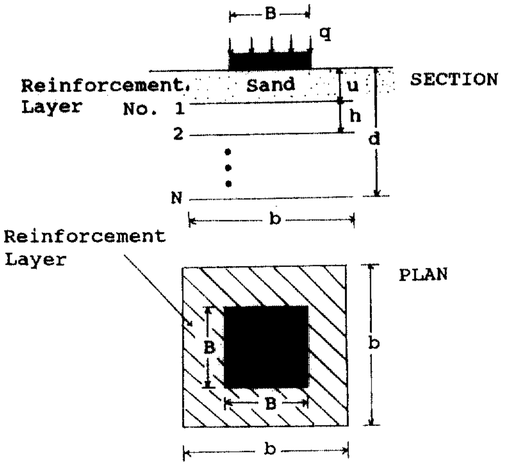

Fig. 1. Square foundation on sand reinforced with N number of reinforcement layers

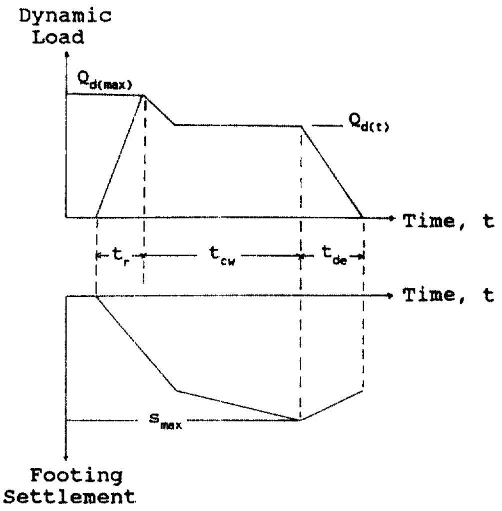

Fig. 2. Nature of transient load to laboratory model foundations

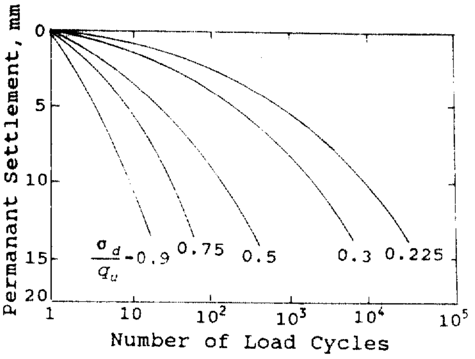

Fig. 3. Plastic deformation due to cyclic loading by Raymond and Komos (1978)

90%, where σ_d=amplitude of cyclic load per unit area of foundation). The load -settlement relationships obtained from these tests are of the nature shown in Fig. 3. For these tests, no sustained static load was applied to the foundation. Such plots may be given by an empirical relation as;

$$\frac{s}{\log N}=a+bs \qquad (1)$$

where a and b=constant and functions of σ_d/q_u

Brummund *et al.*[1] published the laboratory model test results for the permanent settlement of circular foundations on granular soil subjected to vertical vibration. In these tests, the peak acceleration was varied from about 0.1 g to 1.2 g (g=acceleration due to gravity). In spite of these studies, there are several factors which control the permanent settlement of shallow foundations due to dynamic loading which have not yet been clearly identified. A review of current literature shows that no study has yet been conducted to evaluate the load vs. permanent settlement relationship of a shallow foundation supported by sand reinforced with layers of geogrid. The purpose of this paper is to present some recent laboratory model tests related to cyclic load-induced settlement of shallows square foundations (B×B) supported by geogrid-reinforced sand.

2. Parameters Studied in Laboratory Model Tests

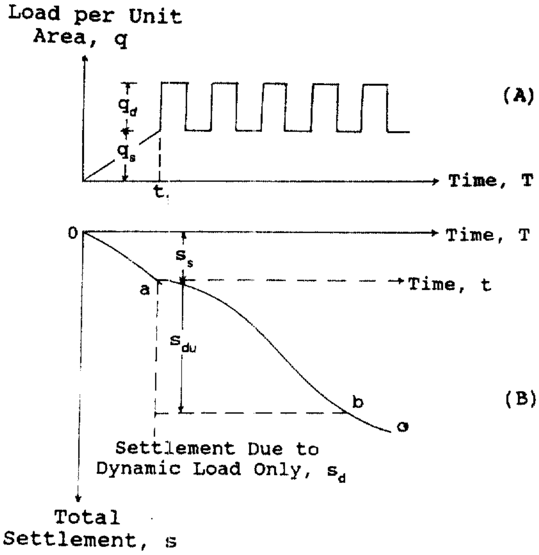

Fig. 4. Variation of load and foundation settlement with time

This study relates to the determination of settlement of the square foundation under cyclic loading. With geogrid reinforcement layers in place (with $d=d_{cr}=1.33B$, $b=b_{cr}=4B$, and $u=0.333B$), if a static load (q_s) is applied on the foundation (Fig. 4a), then the settlement of the foundation with time will take the path o~a as shown in Fig. 4b. The foundation will undergo a settlement of $s=s_s$ (s_s=settlement due to static loading) at time $t=t_1$. It is important to realize that

$$q_s=\frac{q_{ur}}{FS} \qquad (2)$$

where FS=factor of safety
q_s =static load
q_{ur}=ultimate bearing capacity in reinforcement soil

For time $t \geq t_1$, if a cyclic load (q_d) having a period T and an amplitude of q_d is applied to the foundation (Fig. 4a), then it will undergo further settlement which can be represented by path abc (Fig. 4b). For all practical purposes, the maximum settlement due to dynamic loading only is equal to s_{du} (s_{du}=ultimate settlement due to cyclic loading). In this phase of laboratory testing, with various combinations of q_s and q_d, the nature of variation of s_d (s_d=settlement due to cyclic loading)

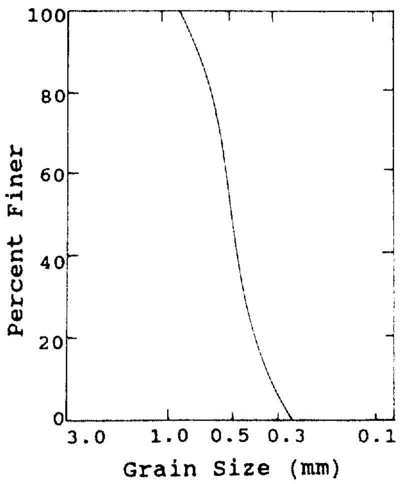

Fig. 5. Grain-size distribution of sand for model tests

and s_{du} has been evaluated.

3. Laboratory Model Tests

The laboratory bearing capacity tests were conducted using a model foundation, made from an aluminum plate, with dimensions (B×B) of 76.2 mm×76.2 mm. A fine round silica sand was used for the model tests, and the grain-size distribution of the sand is shown in Fig. 5. All model tests were conducted at an average relative density, D_r, of 70%.

The average physical properties of the sand during the laboratory tests are given in Table 1.

A biaxial geogrid was used for reinforcement. The physical properties of the geogrid are given in Table 2.

Table 1. Average physical properties of the sand during the model tests

Parameter	Quantity
[a]Maximum dry unit weight, kN/m^3	18.94
[a]Minimum dry unit weight, kN/m^3	14.07
Dry unit weight during model tests, kN/m^3	17.14
Relative density of compaction during model tests, %	70.00
[b]Angle of friction during model tests, deg.	40.30
Note: [a]ASTM test designation D-4253	
[b]From direct shear test	

Table 2. Physical properties of the geogrid

Parameters	Description/quantity
Structure	Punctured sheet drawn
Polymer	PP/HDPE co-polymer
Junction method	Unitized
Aperture size (MD/XMD)	25.4 mm/33.02 mm
Natural rib thickness	0.762 mm
Nominal junction thickness	2.286 mm

Laboratory model tests were conducted in a box measuring 760 mm×760 mm×760 mm. Rough base condition of the model foundation was achieved by cementing a thin layer of sand onto its base with epoxy glue. In conducting the tests, sand was poured into the box in 25.4 mm (1 in.) layers using a raining technique. The accuracy of the sand placement and the consistency of the placement density were checked during raining by placing small cans with known volumes at different locations in the box. Geogrid layers were placed in the sand at desired values of u/B and h/B (h=center-to-center spacing of the geogrid layers as shown in Fig. 1). After completion of the sand placement, the model foundation was placed on the surface of the sand layer. A MTS machine was used for the application of dynamic loads on the foundation. The magnitude of the number of load cycles and the foundation settlement were recorded by a data acquisition system attached to the MTS machine. In order to start a test, a static loading (q_s) with a desired factor of safety (FS) was first applied to the foundation, followed by the application of the cyclic load until the settlement of the foundation became practically constant. The nature of the dynamic loading pattern is shown in Fig. 6. The period, T, of the dynamic load for all tests was 1.0 sec. It is important to point out that for all dynamic tests listed in Table 3, the following constant parameters were used.

Reinforcement: $u/B = h/B = 0.333$

$b/B = (b/B)_{cr} = 4$

$N = 4$[i.e. $d/B = (d/B)_{cr} = 1.333$]

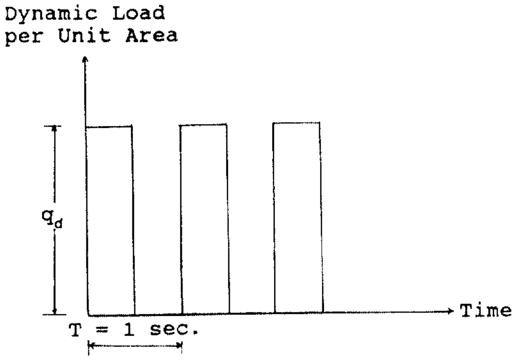

Fig. 6. Pattern of dynamic loading

Table 3. Details of the dynamic tests

Test Series	q_s/q_{ur} (%)	q_d/q_{ur} (%)	Remarks
I-A	33.3	4.36, 10.67, 14.49, 22.33	Reinforced sand
I-B	25.0	4.36, 10.67, 14.49, 22.33	Reinforced sand
I-C	13.2	4.36, 10.67, 14.49, 22.33	Reinforced sand

*q_s = static load, q_d = Cyclic load,
q_{ur} = UBC in reinforcement soil

4. Model Test Results

Figs. 7, 8, and 9 show the relationship between the number of cycles of load application, n, and permanent foundation settlement, s_d, as obtained from Test Series I-A, I-B, and I-C, respectively. These plots are, in general, of the nature show in Fig. 10. The magnitude of s_d/B increases with the number of load cycles (n) to a maximum value of s_{du}/B at $n=n_{cr}$. Beyond $n=n_{cr}$, the settlement due to dynamic load is very small or zero. Hence, for all practical purposes, s_{du}/B can be assumed as the maximum permanent settlement due to cyclic loading. Based on this concept, the magnitude of s_{du}/B and n_{cr} have been determined from Figs. 7, 8, and 9. These are given in Table 4.

As shown in Fig. 10, the maximum settlement due to dynamic loading, s_{du}, may be approximated to be equal to the settlement between $n=0$ and $n=n_{cr}$. Using this definition, the value of s_{du} for various q_s/q_{ur} and q_d/q_{ur} combinations were calculated and are shown in Fig. 11. Based on this fi-

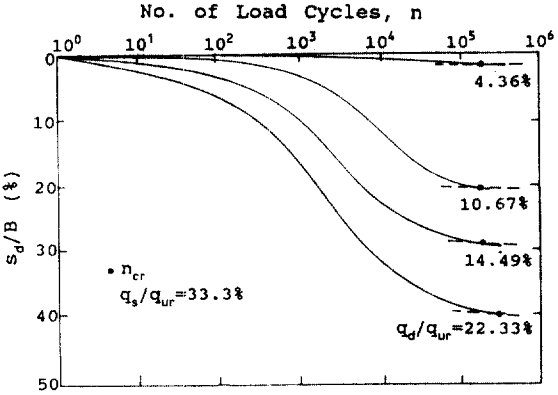

Fig. 7. Variation of settlement vs. number of load cycles for tests on reinforced sand (Test series I-A)

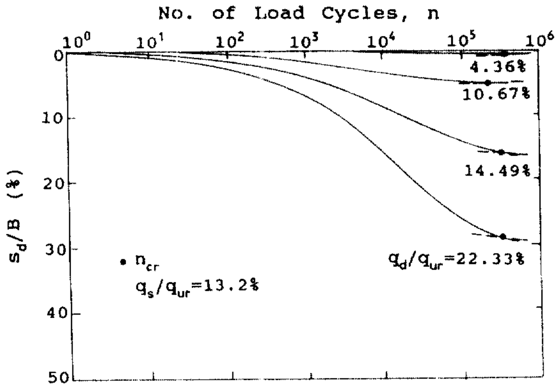

Fig. 8. Variation of settlement vs. number of load cycles for tests on reinforced sand (Test series I-B)

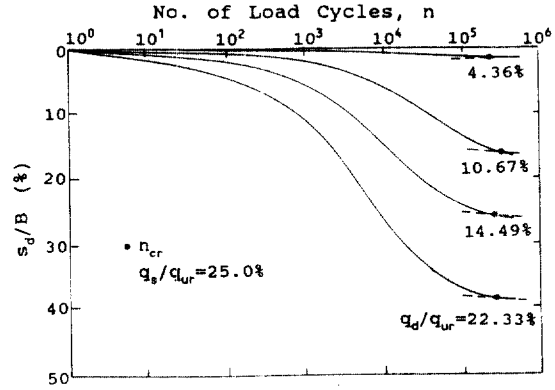

Fig. 9. Variation of settlement vs. number of load cycles for tests on reinforced sand (Test series I-C)

Table 4. Summary of dynamic test results on geogrid reinforced sand (Test series I-A, I-B, and I-C)

q_s/q_{ur} (%)	q_d/q_{ur} (%)	s_{du}/B (%)	n_{cr}	$[n_{cr}]$-Average
33.3	4.36	1.74	2.857×10^5	2.857×10^5
	10.67	20.00	2.143×10^5	
	14.49	28.26	3.036×10^5	
	22.33	39.57	3.393×10^5	
25.0	4.36	1.52	3.393×10^5	3.750×10^5
	10.67	16.09	4.286×10^5	
	14.48	25.22	3.571×10^5	
	22.33	38.48	3.750×10^5	
13.2	4.36	0.87	4.929×10^5	4.268×10^5
	10.67	5.22	2.679×10^5	
	14.48	15.87	4.643×10^5	
	22.33	29.13	4.821×10^5	

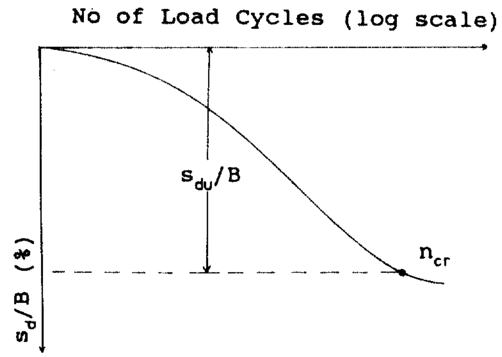

Fig. 10. General nature of the variation of foundation settlement due to dynamic loading

gure, it can be seen that with FS($=q_{ur}/q_s$) varying between 7 and 3 and $q_d/q_{ur}\approx 10\%$, the magnitude of the maximum settlement due to cyclic load may be in the range of 5% to 20% of the width of the foundation. If q_d/q_{ur} is increased to about 20%, the maximum settlement s_{du} for a similar range of FS increases to a range of 30% to 40% of the foundation width.

5. Conclusions

These tests were further extended to evaluate the magnitude of permanent settlement of the foundation where subjected to a cyclic loading. The foundation was supported by a sand layer with optimum geogrid reinforcement. Based on these finding, the following general conclusions can be drawn.

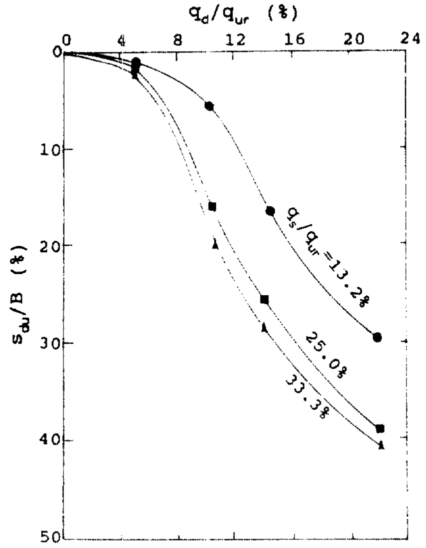

Fig. 11. Variation of s_{du}/B with q_d/q_{ur} and q_s/q_{ur}

1. For a given value of q_s/q_{ur} and n, the magnitude of s_d/B increases with the increase of q_d/d_{ur}.
2. For a given value of q_d/d_{ur} and n, the magnitude of s_d/B increases with the increase of q_s/q_{ur}.
3. For a given value of q_d/d_{ur}, the magnitude of n_{cr} decreases with the increase of q_s/q_{ur}.
4. For a given value of q_s/q_{ur}, the magnitude of n_{cr} is approximately constant.

Further studies are necessary to quantify parameters for actual design conditions. The maximum possible BCR, $BCR_{(max.)}$ obtained will also be a factor of the type and stiffness of the geogrid. It will be necessary to conduct model tests of the type done in this study using geogrids of varying stiffness before a reasonable working method can be established for field work.

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