Elastic modulus of granular soil-geogrid composite from cyclic plate load tests

Module d'élasticité d'un composite sol-geogrille à partir d'essais de chargement cycliques à la plaque

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ABSTRACT
The elastic settlement of foundations and other structures, bases and subbase layers of paved and unpaved highways, and runways of airports is an important consideration in the design and construction process. Laboratory and field studies have shown that geogrid can be used as a reinforcing material in granular soil to increase the stiffness of the soil-geogrid composite system and thereby reduce elastic settlement. This implies that the modulus of elasticity of the soil-geogrid system is increased due to reinforcement. In order to evaluate the modulus of elasticity of the granular soil-geogrid composite in the field, cyclic plate load tests were conducted at a site at the Incheon International Airport (Korea) during its construction phase. The test results and the method for obtaining the modulus of elasticity are presented in this paper.

RÉSUMÉ
Le tassement élastique des couches de base et de sous-base des routes pavées et non pavées, et des pistes d'aéroports est une préoccupation importante dans les processus de conception et de construction. Des études au laboratoire et sur le terrain montrent que les géogrilles peuvent être employées comme matériaux de renforcement dans les sols granulaires afin d'augmenter la rigidité du système composé de sol-géogrille permettant ainsi de réduire le tassement. Ceci implique une augmentation du module d'élasticité du système sol-géogrille par le renforcement. Aftin d'évaluer le module d'élastique du composé sol-géogrille , des essais de chargement cycliques à la plaque ont été effectués à un emplacement à l'aéroport international d'Incheon (Corée) pendant sa phase de consruction. Les résultats de ces essais et la méthode utilisée pour obtenir les modules d'élasticité sont présentés dans cet article.

Keywords : Plate load test, modulus of elasticity, geogrid reinforcement, granular soil, elastic settlement

1 INTRODUCTION

Elastic settlement under imposed load is an important parameter in the design and construction of shallow foundations, base course of paved and unpaved roads, and runways and taxiways of airports. For calculating the elastic settlement under a certain type of loading, one needs to know the dimensions of the loaded area, as well as the Poisson's ratio and modulus of elasticity of the soil under consideration. For example, the elastic settlement at any depth z under the corner of a uniformly loaded flexible rectangular area [$S_e(z)$] with a width B and length L can be given as (Harr 1966)

$$S_e(z) = \frac{Bq}{2E_s}(1-\mu_s^2)\left(A' - \frac{1-2\mu_s}{1-\mu_s}B'\right) \tag{1}$$

where

$$A' = \frac{1}{\pi}\left(\ln\frac{\sqrt{1+m^2+n^2}+m}{\sqrt{1+m^2+n^2}-m} + m\ln\frac{\sqrt{1+m^2+n^2}+1}{\sqrt{1+m^2+n^2}-1}\right) \tag{2}$$

$$B' = \frac{n}{\pi}\tan^{-1}\frac{m}{n\sqrt{1+m^2+n^2}} \tag{3}$$

$$m = \frac{L}{B} \tag{4}$$

$$n = \frac{z}{B} \tag{5}$$

q = uniform load per unit area
E_s = modulus of elasticity of soil
Similarly, the elastic settlement at any depth z below the center of a uniformly loaded flexible circular area of radius R can be given as

$$S_e(z) = \frac{2Rq(1-\mu_s^2)}{E_s}\left(\sqrt{1+n'^2}-n'\right)\left[1+\frac{n'}{2(1-\mu_s)\sqrt{1+n'^2}}\right] \tag{6}$$

where

$$n' = \frac{z}{R} \tag{7}$$

The elastic settlement at the surface (i.e. z = 0) can be obtained from Equations (1) and (6) as
Below the corner of the rectangular area:

$$S_e(z=0) = \frac{Bq}{2\pi E_s}(1-\mu_s^2)\left(\begin{array}{l}\ln\frac{\sqrt{1+m^2}+m}{\sqrt{1+m^2}-m}\\ +m\ln\frac{\sqrt{1+m^2}+1}{\sqrt{1+m^2}-1}\end{array}\right) \tag{8}$$

and below the center of a circular area:

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$$S_e(z=0) = \frac{2Rq}{E_s}(1-\mu_s^2) \tag{9}$$

During the past ten to fifteen years, several laboratory tests results related to the ultimate and allowable bearing capacities of shallow foundations supported by geogrid-reinforced sand have been published (Fig. 1). The results show that the inclusion of geogrid as reinforcement helps reduce the settlement of foundations under static and dynamic loading. Thus, a reasonable estimate of the reduced elastic settlement of the geogrid-reinforced soil at the surface (z = 0) can be obtained from relationships such as Equations (8) and (9) if a modulus of elasticity of the soil-geogrid system (E_{sg}) in the zone of stress influence can be obtained and substituted for E_s. Poisson's ratio is not a very sensitive parameter and can be assumed for reasonable results. However it is important to realize that the magnitude of E_{sg} of the stabilized soil will be a function of several parameters (Fig. 1) including: (a) stiffness of the geogrid, (b) number of geogrid layers in the zone of influence (N), (c) location of the first layer of geogrid below the bottom of the loaded area (u/B), (d) width of geogrid layers (b/B), (e) distance between consecutive layers of geogrid (h/B), and (f) total depth of reinforcement (d/B).

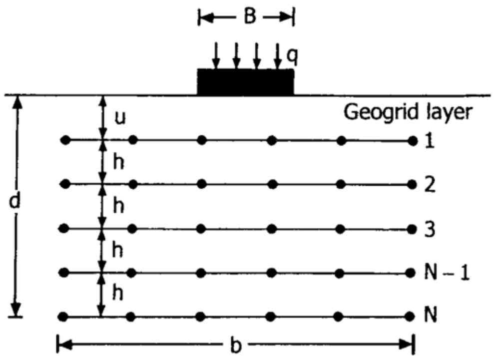

Figure 1. Surface foundation on geogrid-reinforced sand.

This paper reports the results of four cyclic plate load tests conducted in the field on a granular soil pad both with and without geogrid reinforcement layers to observe the effects of various parameters on the modulus of elasticity of the soil.

2 PROCEDURE TO OBTAIN MODULUS OF ELASTICITY FROM CYCLIC PLATE LOAD TESTS

Cyclic plate load tests in the field are conducted by applying step loads to a test plate, unloading the test plate, and then reloading it. As shown in Fig. 2, when a plate is first loaded to a uniformly distributed stress level (q_1), then unload and reloaded, the elastic rebound of the soil is $S_{e(1)}$. Similar loading and unloading can be done at various stress levels (i.e. q_2, q_3, . . .) to obtain the corresponding elastic rebounds of $S_{e(2)}$, $S_{e(3)}$, ... The variation of q can be plotted against the corresponding S_e. The plot will be approximately a straight line (Fig. 3). The slope of the line is

$$C_z = \frac{q}{S_e} \tag{10}$$

where C_z = coefficient of elastic uniform compression.

Barkan (1962) provided a theoretical relationship for C_z in the form

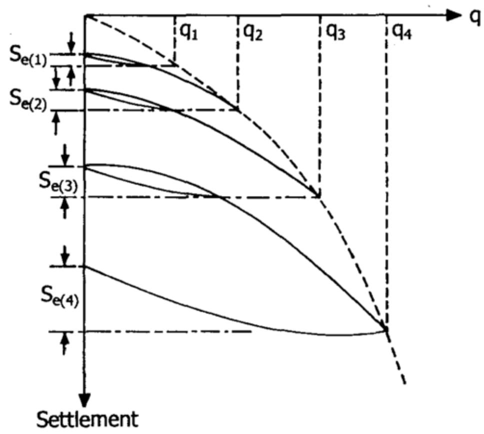

Figure 2. Plot of nature of variation of settlement vs. load per unit area from plate load tests.

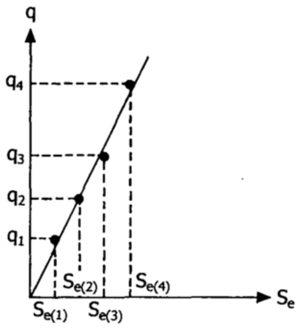

Figure 3. Plot of q vs. S_e to obtain the coefficient of elastic uniform compression.

$$C_z = 1.13\frac{E_s}{1-\mu_s^2}\frac{1}{\sqrt{A}} \tag{11}$$

where A = area of the test plate.

The magnitude of the modulus of elasticity can thus be obtained as

$$E_s = 0.885C_z(1-\mu_s^2)\sqrt{A} \tag{12}$$

In most cases, the magnitude of E_s determined by Equation (12) will be for a strain level of about 10^{-4} to 10^{-3} (Prakash 1981). This is the most likely strain level to calculate the elastic settlement of shallow foundations.

3 FIELD TEST ARRANGEMENT

A total of four cyclic plate load tests were conducted on four compacted granular soil pads at the site of the Incheon International Airport, South Korea. The airport was being constructed on land reclaimed from the ocean. Figure 4 shows the schematic diagram of the test arrangement. The granular soil pads were each 0.45m high and measured 4m × 4m at the top. The granular soil pads were constructed over a layer of dredged soil having a thickness of 0.5m. A layer of geotextile measuring 3m × 3 m was placed at the interface of the granular pad and the dredged soil. Desired layers of geogrid (each measuring 2m × 2m) were placed in the granular pad.

Figure 5 gives the grain-size distribution of the soil layers shown in Fig. 4. The loading plate used for the tests had a diameter of 0.3m (B). The physical properties of the geotextile and geogrid used for soil reinforcement are given in Table 1, and details of the plate load tests are given in Table 2. The geotextile layer was used primarily for separation purposes.

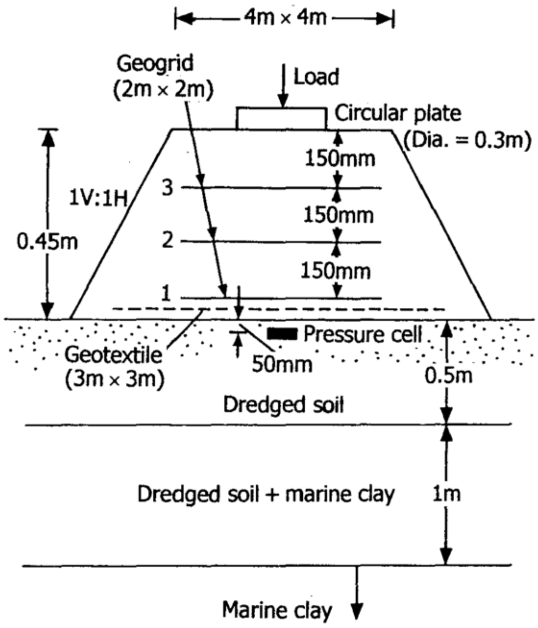

Figure 4. Schematic diagram of field load test arrangement.

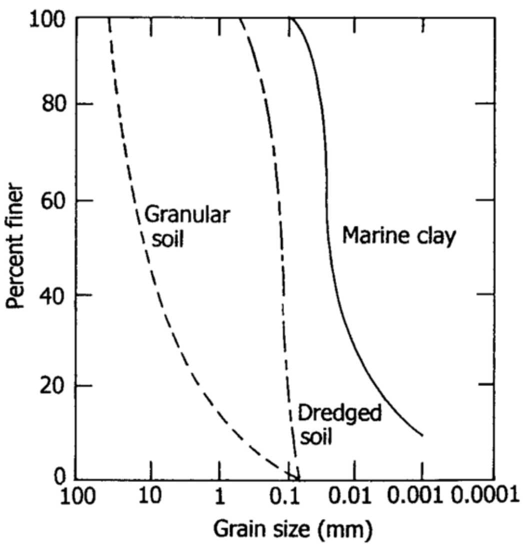

Figure 5. Grain-size distribution of soil layers shown in Figure 4.

Table 1. Physical properties of geosynthetics used for soil reinforcement

Property	Geogrid	Geotextile
Polymer type	Polypropylene	Polyester
Manufacturing type	Bi-axial	Non-woven
Product size	4m × 50m	8.5m × 50/100m
Mass per unit area (g/m^3)	650	700
Thickness (mm)	6.5 (junction)	4.5
Maximum tensile strength (kN/m)	MD-37.6; CD-40.8	1.745
Yield point elongation (%)	MD-10.1; CD-12.4	50 to 120
Tensile strength at 2% elongation (kN/m)	MD-20.2; CD-14.1	——
Tensile strength at 5% elongation (kN/m)	MD-32.3; CD-27.5	——
Aperture size (mm)	34-MD × 27-CD	——
Carbon black content (%)	2	——

Note: MD—machine direction; CD—cross-machine direction

Table 2. Details of plate load tests

Test No.	Reinforcement details
1	No reinforcement
2	Reinforcement layer No. 1 (i.e., one layer of geotextile and one layer of geogrid only)
3	Reinforcement layers No. 1 and No. 2
4	Reinforcement layers No. 1, No. 2 and No. 3

Omar et al. (1993) demonstrated that, for square or circular loading, the depth of reinforcement d for significant beneficial effect is about 1.5B (Fig. 1). Also, for realization of any benefical effect of reinforcement, the width of reinforcement (b) should not be more than 4B to 5B. For all of the field tests under consideration, d/B = 3 and b/B = 6.66. Hence the entire geogrid reinforcement were within the significant zone of influence of loading for elastic settlement consideration.

4 PLATE LOAD TEST RESULTS

Figure 6(a) shows the results of plate load test No. 1 which was conducted on unreinforced soil. The elastic rebounds at various stress levels obtained from the test is plotted in Fig. 6(b). The coefficient of elastic uniform compression obtained from Fig. 6(b) is 30.25×10^4 kN/m^2. From Equation (12), assuming $\mu_s \approx 0.3$,

$$E_s = 0.885 C_z (1-\mu_s^2)\sqrt{A}$$
$$= (0.885)(30.25\times10^4)(1-0.3^2)\sqrt{(\pi/4)\times0.3^2} = 64{,}770\,\text{kN/m}^2$$

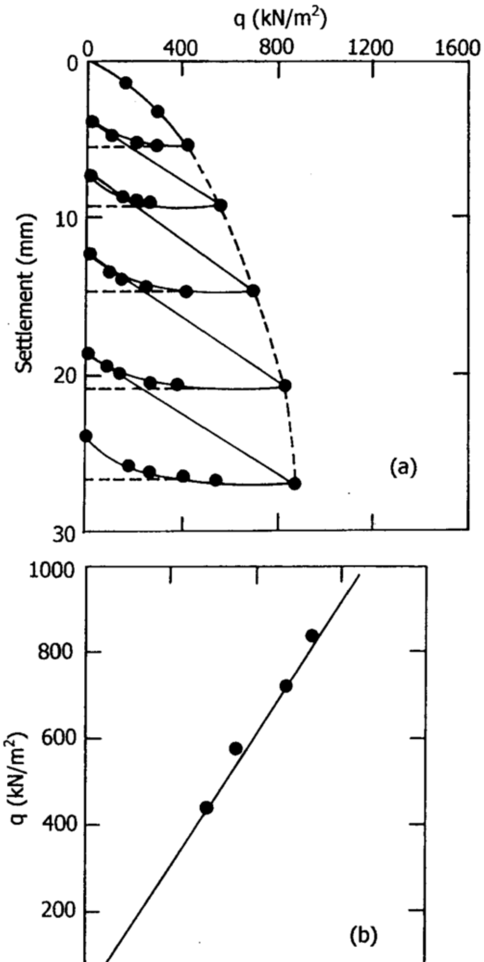

Figure 6. Results of plate load test No. 1 (unreinforced soil).

Figure 7 shows results of a typical cyclic plate load test on reinforced soil (test No. 3). Similar plots were obtained from test Nos. 2 and 4. Figure 8 shows the plots of q vs. S_e for all tests with reinforcement. Assuming $\mu_s = 0.3$ and using Equation (12), the magnitudes of E_{sg} were calculated and are presented in Table 3. From this table the following general observations may be made:

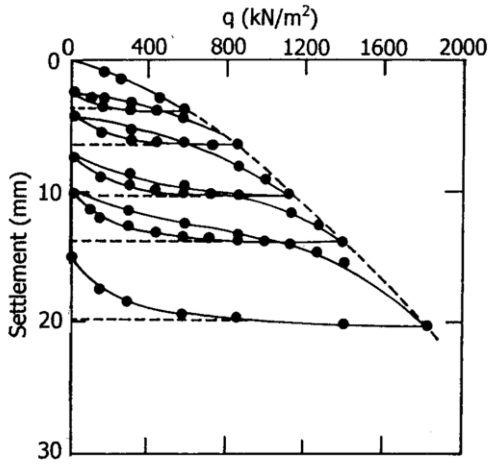

Figure 7. Plate load test results on reinforced soil (test No. 3).

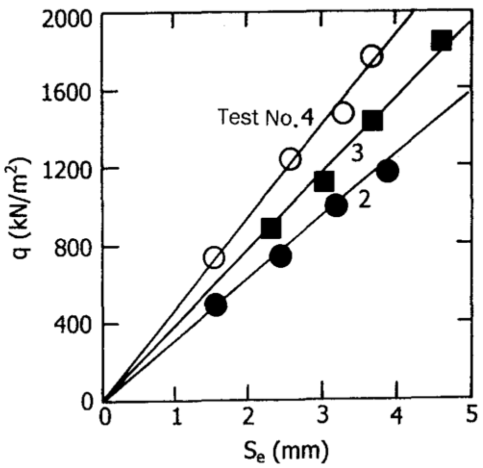

Figure 8. Plot of q vs. S_e for tests with geogrid reinforcement.

Table 3. Summary of test results with geogrid reinforcement ($\mu_s = 0.3$)

Test No.	C_z (kN/m^2)	E_{sg} (kN/m^2)	E_{sg}/E_s
2	33.1×10^4	70,830	1.094
3	39.1×10^4	83,670	1.292
4	46.7×10^4	99,940	1.543

1. The inclusion of geogrid layers as reinforcement helps to increase the overall stiffness and, thus, the modulus of elasticity of the soil.
2. Keeping the total depth of reinforcement (d) constant, the modulus of elasticity gradually increases with the increase in the number of layers of reinforcement.
3. For this study, with three layers of reinforcement in place, E_{sg} increased by about 54%. With only one layer of reinforcement at d = 1.5B, the magnitude of E_{sg} increased by only 9%. This was expected since the zone of stress influence for a circular plate is about 1.5B below the plate.

5 CONCLUSIONS

A limited number of cyclic plate load test results on granular soil pads both with and without reinforcement were presented. Based on the results of the plate load tests, the variation of the modulus of elasticity of the mechanically stabilized earth was determined. For the present study, the maximum depth of reinforcement was kept at 1.5 times the diameter of the test plate; however the number of reinforcement layers was varied. Results show that, for the same maximum depth of reinforcement, the modulus of elasticity increases with the number of layers in place (i.e., with the decrease in the spacing between reinforcing layers). The modulus of elasticity of the mechanically stabilized material can be used to estimate the elastic settlement of the foundation.

Further study is recommended to determine the optimum values of u/B, b/B and h/B for deriving the maximum benefit to improve the modulus of elasticty of the mechanically stabilized soil mass below the foundation.

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