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DYNAMIC PLATE LOADING TESTS ON GEOGRID-REINFORCED SUBGRADES

EXAMENS DE PLAT DYNAMIQUE CHARGE SUR GEOGRID ARME FONDEMENT

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SYNOPSIS: The objective of this experimental study was to determine the effect of various parameters on the load capacity and settlement of geogrid-reinforced earth slabs subjected to dynamic loading. The parameters varied were: the number of layers of reinforcement, the width of the reinforcement, and the amplitude and frequency of the dynamic loading. To evaluate the overall improvement of a reinforced soil to an unreinforced soil the load cycle ratio (LCR) was defined as the ratio of the dynamic load capacity of the reinforced soil (DLCR) to the dynamic load capacity of the unreinforced soil (DLCU). It was found that the LCR increased by 150% to 300% as the number of layers of reinforcement increased from 2 to 4 and a 140% increase in the LCR for a width of reinforcement three times that of the plate. Insertion of geogrid reinforcement in the subgrade increased the dynamic load capacity and decreased the settlement.

INTRODUCTION

Shallow foundation designs for dynamic loadings due to vibrating machinery have proven to be extremely difficult. Such foundations are usually massive concrete blocks placed on granular soils pre-compacted to extremely high relative densities. Other vibrating machine foundations employ special vibration isolators in an effort to reduce the dynamic forces transmitted to the soil.

This paper will present the results of an investigation by the authors to see if the inclusion of geogrid reinforcement into a foundation soil (already a proven methodology for increasing foundation bearing capacity under static loading conditions) would improve its load bearing characteristics under dynamic loading.

BACKGROUND

The topic of soil dynamics is very complex and different theories have evolved to describe it. The spring-mass-dashpot theory provides a simplified model of a conventional soil foundation system where the footing is represented by a weighted block of mass m and the soil is represented by an elastic spring of stiffness K and a viscous damping coefficient c. The semi-infinite elastic half space theory assumes the footing to be of mass m and the soil to be homogeneous, isotropic and elastic with a shear modulus G and a Poisson's ratio μ. The lumped-parameter system combines the simplicity of the spring-mass-dashpot theory with the accuracy of the elastic half space theory.

Guidelines for dynamic foundation design were issued by the Indian Standard Institution based on Indian and European Standards in 1964 and revised in 1969. Some of these guidelines are as follows:

(1) Resonance should be avoided. The ratio of the dynamic machine operating frequency ω to the natural frequency of the soil-foundation system ω_n should be less than 0.5, if $\omega > \omega_n$ the ratio ω to ω_n should be greater than 2.0.

(2) Soil stress below the base of a dynamically loaded footing at maximum force amplitude should not exceed 80% of the allowable static bearing capacity. Vesic et al (1965) yield more conservative values and recommend that the peak dynamic amplitude should be kept at 50% to 70% of the allowable static bearing capacity for satisfactory foundation performance.

In order to reduce dynamic settlements in granular soil Whitman and Richart (1967) recommended precompacting the foundation soil to a high relative density. The purpose of precompaction is to provide a severe dynamic loading to the soil during site preparation than is expected during the operating life of the installed vibrating machines. In addition, the compacted soils have improved damping characteristics and a more linear-elastic response. Seed et al (1986) have shown that relative densities as low as 65% may also be effectively used.

THE EXPERIMENT

A series of 30 model dynamic plate loading tests were performed in a square stiffened wooden box 1.22 m wide and 0.92 m deep. Based on the results of over 280 prior model static plate loading tests, it was determined that this size test model maximizes edge effects. The soil used was a poorly graded sand (SP) at a relative density of 65%. See Table 1 for properties of the soil. This relative density was used based on recommendations of Seed et al (1986). Using the fixed-free rod method of Richart et al (1970) it was determined that the natural frequency of the sand at 65% relative density was approximately 50 Hz. The dynamic loading was applied by a

Cunningham heavy duty cylinder connected to a hydraulic power unit and controlled by a programmable logic converter (PLC) from Divelbliss, Inc. This dynamic loading was applied for 1000 load cycles vertically and concentrically to a square aluminum plate 0.31 m wide and 26 mm thick located at the surface of the sand. The loading frame was of sufficient mass and bracing to prevent resonance with a natural frequency of approximately 43 Hz. For those tests requiring static loading an Enerpac hydraulic cylinder of 222 kN capacity was used and the load recorded on a 90 kN capacity load ring. The settlement of the plate was measured by four dial gauges placed at each corner of the plate. These gauges had a 51 mm capacity with a 25 μm sensitivity. The geogrid reinforcement used was the Tensar BX-1100 biaxially oriented grid, see Table 2. These grids were placed in the sand in square sheets concentrically below the plate with no sheet being used more than once. The soil was placed in lifts 76 mm thick. Five series of plate loading tests were performed.

Table 1. Properties of the Subgrade Soil

Uniformity Coefficient, C_u	1.90
Coefficient of Gradation, C_c	1.23
Effective Size, D_{10}	0.086
Specific Gravity, G_s	2.66
Minimum Dry Unit Weight, $\gamma_{d(min)}$ (kN/m^3)	13.10
Maximum Dry Unit Weight, $\gamma_{d(max)}$ (kN/m^3)	15.65
Angle of Internal Friction, ϕ, (deg.)	38

Test Series A

This initial test series consisted of static plate loading tests performed on the unreinforced sand. A plot of bearing pressure q versus the settlement ratio s/B, where: s is the average settlement of the plate and B is the width of the plate, yielded a static bearing capacity of 324kPa and an s/B of 0.07. This was the point on the curve where a steep linear slope began, since no specific yield point was exhibited, see Fig. 1. For a square plate 0.31 m wide the static bearing capacity force of the unreinforced soil P_{su} was 31 kN.

Table 2. Properties of Tensar BX1100 Grid

Chemical Composition	Weight (N/m^2)	Characteristic Tensile Strength (kN/m)
High density polypropylene	1.96	20.5^{+}/12.5*

$^{+}$ Across Roll Width (Transverse)
* Along Roll Width (Longitudinal)

Test Series B

This test series consisted of dynamic plate loading tests on unreinforced sand. A square wave pulse loading of amplitude P_o equal to 25% of P_{su} was used with a frequency of 1 Hz and a period of 1 second, see Fig. 2. This loading was chosen to simulate a low frequency, repetitive machine load. A resonant condition did not exist for either the loading frame or sand since the frequency of dynamic loading was below the natural frequencies of the loading frame and sand.

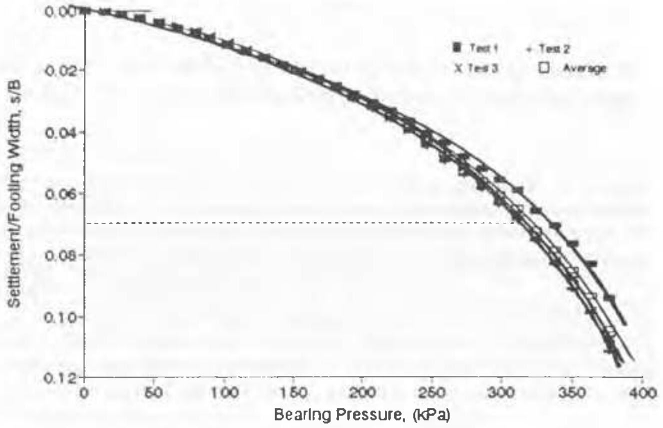

Fig. 1. Test Series A - s/B vs. bearing pressure

Since a formal definition of dynamic bearing capacity does not exist, the authors determined the dynamic load capacity of the unreinforced soil (DLCU) as follows. From the data presented in Fig. 3, it can be observed that no specific yield point was exhibited. Therefore, the DCLU was taken at the point where the curves exhibited a steep linear slope. For this test series the DCLU was 565 load cycles, which occurred at an S/B of 0.072.

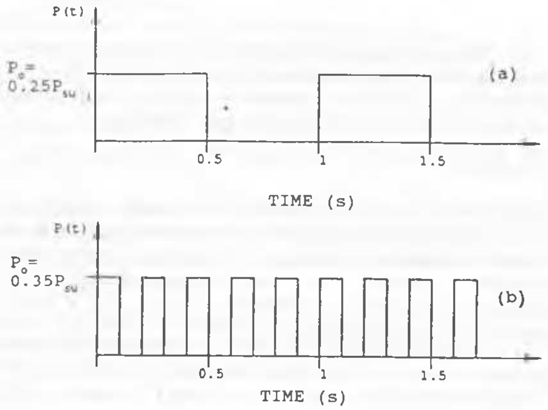

Fig. 2. Dynamic load functions. Test series B and C (f=1 Hz, T=1 sec.) in (a), test series D and E (f=5Hz, T=0.2 sec.) in (b)

Test Series C

This test series consisted of dynamic plate loading tests on a geogrid-reinforced sand. The dynamic parameters were identical to those used in Test Series B. The depth to the top layer of reinforcement, u, and the spacing of the reinforcement, Δz were kept at 76 mm or $u/B = \Delta z/B = 0.25$. Two parameters were varied, the number of layers of reinforcement N and the width of a square sheet of reinforcement b or b/B. The dynamic load capacity of the reinforced soil (DLCR) was obtained by determining the number of load cycles it took to reach the same s/B (0.072) equal to the dynamic load capacity of the unreinforced soil (DLCU), see Figs. 4 and 5. In order to be able to express and compare results the load cycle ratio (LCR) was defined as

$$LCR = \frac{DLCR}{DLCU} \qquad (1)$$

Note the LCR is analogous to the bearing capacity ratio (BCR) introduced by Binquet and Lee (1975) for static testing.

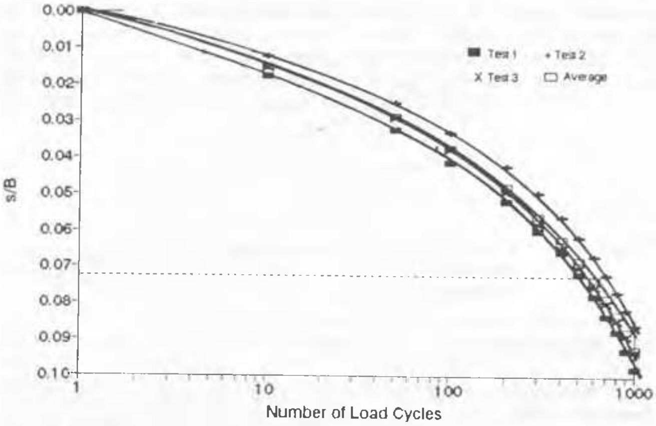

Fig. 3. Test Series B - s/B vs number of load cycles

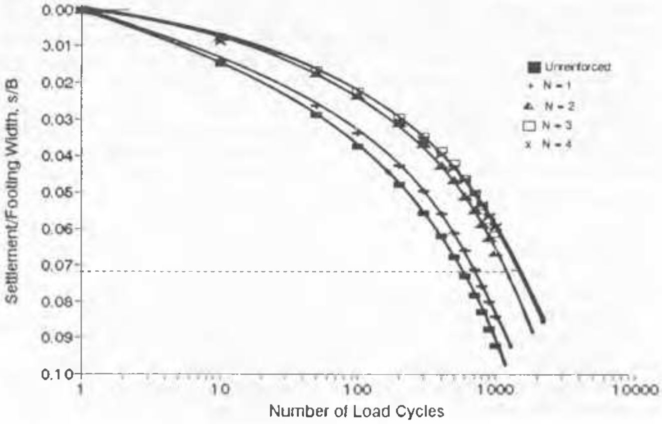

Fig. 4. Test Series C - s/B vs. number of load cycles for N=1 to 4, b/B=2.5, $u/B = \Delta z/B = 0.25$

Test Series D

This test series consisted of dynamic plate loading tests on an unreinforced sand. The square wave pulse loading had a maximum amplitude P equal to 35% of P_{su} with a frequency of 5 Hz and a period of 0.2 seconds, see Fig 2(b). The maximum load amplitude used in this test series is 40% higher than that used in Test Series B and C. This more intense dynamic load can be used to simulate a shallow foundation load caused by a forging hammer or other powerful repetitive machine. A resonant condition did not exist for either the loading frame or sand since the applied dynamic loading was well below the natural frequencies. The DLCU was determined in the same manner as in Test Series B and resulted in 260 load cycles occurring at an s/B of 0.112. Larger amplitude loads yield larger settlements, however, since the actual load time is reduced (0.2 sec. period), there is less work actually being transmitted to the soil. This means that the soil does not yield until more settlement has occurred than under a low amplitude, longer load time function.

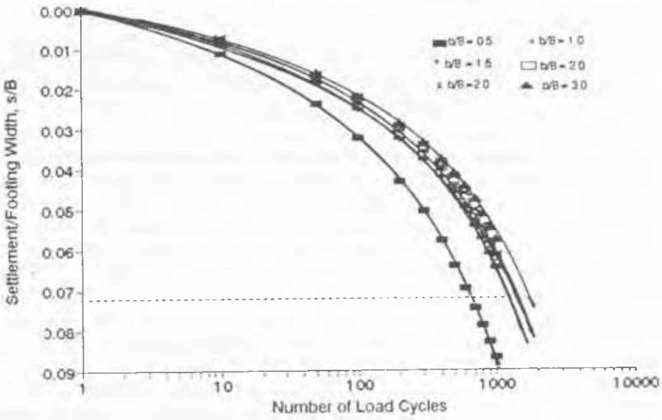

Fig. 5. Test Series C - s/B vs. number of load cycles for b/B=0.5 to 3.0, N=3, $u/B = \Delta z/B = 0.25$

Test Series E

The final test series consisted of dynamic plate loading tests on a geogrid-reinforced sand. The dynamic parameters were identical to those used in Test Series D. The values of u/B and $\Delta z/B$ were both kept constant at 0.25 with b/B at 2.5 while the number of layers of reinforcement N was varied. The DLCR was obtained by determining the number of load cycles it took to reach the same s/B (0.112) equal to the dynamic load capacity of the unreinforced soil (DLCU).

TEST RESULTS

Effect of Number of Layers of Reinforcement

The variation of LCR with N for Test Series C is given in curve (a) of Fig 6. This plot shows there is little improvement in dynamic load capacity for one layer of geogrid reinforcement. However, for N greater than or equal to 2 there is a dramatic improvement in LCR from about 2 for N=2 to about 2.5 for N=4. This indicates that the geogrid-reinforced soil can endure 2 to 2.5 times the number of loading cycles before yielding than it could endure if the soil were unreinforced.

Curve (b) of Fig. 6 is the variation of LCR with N for Test Series E. It can be seen that there is nearly a linear increase in the dynamic load capacity with increasing N, with the LCR increasing from 1.5 for N=1 to 3.9 for N=4. Test

Series E has higher dynamic load capacities than Test Series C and the LCR increases at a much slower rate as N approaches 4 in Test Series C. Both of these results may be explained by the fact that Test Series E used a much larger dynamic load pulse than was used in Test Series C.

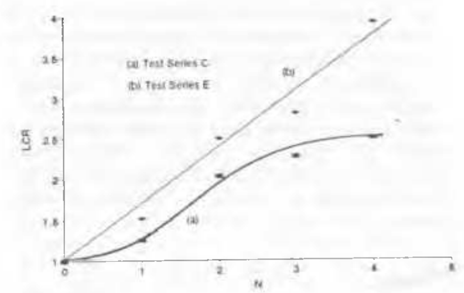

Fig. 6. LCR Variation with the number of reinforcing layers, b/B=2.5, u/B=Δz/B=0.25

If a comparison is made of s/B at failure for Test Series C and E an additional explanation of these test results can be made. For Test Series C, the dynamic load capacity was assumed to occur at s/B=0.072 or 22 mm; while for Test Series E it was obtained at s/B=0.112 or 34 mm. The differ- ence in settlement is 12 mm. Considering that the first layer of reinforcement is 76 mm below the base of the plate, this additional 12 mm of settlement places the base of the plate for Test Series E closer to the soil-grid system than Test Series C. This allows the geogrid near the base of the plate to work more effectively, thereby increasing the LCR for Test Series E.

Another useful basis for comparing the behavior of dynamically loaded reinforced to unreinforced soils is through an analysis of average settlements. The variation of s/B with N is given in Fig. 7. These curves indicate there is a steady decrease in settlement with increasing N. For example, for Test Series C at 600 load cycles, settlements are reduced by 10% for N=1 increasing to a 36% reduction for N=4. In addition, for Test Series C there is little reduction in settlement between N=3 and N=4. This may be an indication that for this load function, there would be little or no improvement in the soil's overall dynamic behavior if a fifth layer of reinforcement was added. For Test Series E at 400 load cycles, settlements are reduced 18% for N=1 increasing (almost linearly) to a 48% reduction for N=4. The settlements for Test Series E decreased much more than for Test Series C. In addition, there is little indication that the Test Series E curves are "leveling off" beyond N=4.

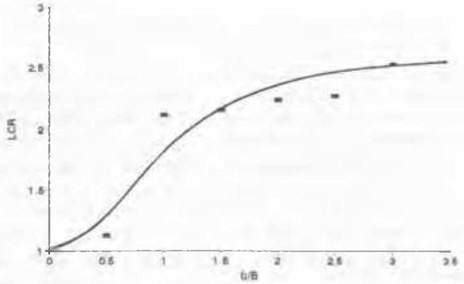

Fig. 8. LCR variation with width ratio, N=3, u/B=Δz/B=0.25

Effect of the Width Size of a Square Sheet of Reinforcement

Fig. 8 shows the variation of LCR with b/B for Test Series C. This plot can be divided into two regions. In the first region, b/B=0.5, there is little improvement in the soil's dynamic load capacity; and in the second region, b/B from 0.5 to 3.0, there is a gradual increase in LCR from 2 to 2.4. For b/B less than 1.0, the sheets of geogrid reinforcement are not wide enough to be anchored by the shear and compressive forces developed beneath the plate. Subsequently, the tensile forces developed in the soil can not be resisted effectively. In addition, it was observed that a reduction in settlement occurred with increasing width ratio. For b/B less than 1.0 there was only a moderate reduction in settlement.

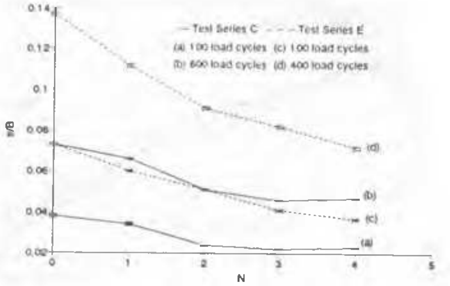

Fig. 7. Variation of s/B with the number of reinforcing layers, b/B=2.5, u/B=Δz/B=0.25

5 CONCLUSIONS

As was indicated earlier, the design of shallow foundations for dynamic loading is extremely difficult. It has been shown in this paper that the inclusion of geogrid reinforcement in a sand subgrade had a positive effect on the behavior of the soil when subjected to dynamic loading. The overall load carrying capacity was increased and settlement decreased. The dynamic load capacity of the soil increased with an increase in the number of layers of reinforcement and with an increase in the size of a square sheet of reinforcement. In addition, for an increase in the amplitude and frequency of loading the dynamic load capacity of the soil increased.

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