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Technical Note

Strain measurement and interpretation of stabilising force in geogrid reinforcement

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Abstract

The stabilising force provided by a layer of geogrid reinforcement embedded in the body of a sloped fill subjected to loading from a footing located near the crest was investigated through a laboratory model study and the results are reported in this paper. This study indicates that the geogrid reinforcement could be instrumented more reliably with strain gauges installed in pairs, i.e., on top and bottom faces of the geogrid, at each location across the geogrid reinforcement and the use of the average strain minimises the influence of flexural strains in the geogrid. If only one strain gauge per location is used, the tensile strain and geogrid force estimated on the basis of nominal stiffness would not be accurate particularly at low load levels and considerable caution is required when using such an approach. The study demonstrates that the accuracy of the estimated stabilising force in the geogrid reinforcement could be enhanced by calibrating each pair of gauges as installed in position since each gauge installed at different locations across a geogrid sample would behave differently. Details of a relatively simple tensile testing method developed for calibrating these gauges and the use of calibration results for assessing the gradual development of stabilising force in the reinforcement in relation to the foundation load are discussed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Geogrid strain; Reinforced slopes; Footings; Electrical strain gauges; Reinforcement stabilising force; Tensile testing of geogrids; Laboratory tests

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1. Introduction

Accurate estimation of tensile forces and strains developed in geosynthetics when used as reinforcement of a soil structure under working conditions is an essential requirement of engineering design. Bonded electrical resistance strain gauges are often used for measuring the strains developed in geosynthetic reinforcement in laboratory experiments (e.g., Abdelhalim, 1983; McGown et al., 1984 ; Bathurst et al., 1989) and in field structures (e.g., Rowe and Gnanendran, 1994; Rowe and Mylleville, 1996) for studying their behaviour under working conditions.

Specific problems in using strain gauge techniques in geosynthetics, when used as reinforcement in soil structures, include the choice of a suitable adhesive, the method of installation and the difficulty of relating the measured local strain to stresses/forces in the geosynthetic. Extensive research carried out over the past two decades has resulted in selecting appropriate adhesives and devising fairly reliable methods for installing strain gauges on geogrids and geotextiles (see e.g., Sluimer and Risseew, 1982; Abdelhalim, 1983; McGown et al., 1984; Gnanendran, 1987; Schimelfenyg, et al., 1990; Rowe and Gnanendran, 1994). Relating the measured local strain to the force developed in the geosynthetic and to the overall stress–strain (or load settlement) behaviour of the reinforced soil structure, however, still presents a problem of concern. A reliable method for instrumenting a geogrid reinforcement with strain gauges and relating the measured strains to the overall behaviour of a reinforced sloped fill subjected to a footing load was investigated through laboratory model tests. In particular, the load-settlement behaviour of a footing located near the crest of this reinforced slope and the progressive development of stabilising force in the geogrid reinforcement up to occurrence of failure were studied. Strain gauges were installed in pairs (i.e., on two faces of geogrid) and along the length of reinforcement to monitor its performance in the sloped fill structure. These gauges were calibrated by a specially designed tensile test. Details of the calibration tensile test, instrumentation used for the laboratory testing and the results of this investigation are reported in this paper.

2. Measuring geogrid tensile strain and estimating the stabilising force

Reinforcing elements in soil structures provide improved stiffness via two modes; namely: (i) in plane tension and (ii) in bending. In geogrid reinforcement, the extensional stiffness is usually much greater than the flexural counterpart. When the geogrid is used over a large plan area (i.e., with area dimensions much larger than, say, the grid opening size) the dominant reinforcement action is derived via the extensional stiffness.

If a geogrid sample instrumented with a strain gauge is incorporated in a soil structure as reinforcement, the measurements derived from strain gauges will give the resultant strain due to changes in both "global" extension and "local" bending of the geogrid. From an overall perspective, the reinforcing effect provided by the geogrid is however due to tension only and therefore the strain caused by tension alone needs to be measured. Although geogrid reinforcement is usually placed flat and horizontal, flexural changes are likely to occur during construction and subsequent application of the load. Therefore, the influences of flexural changes on the measured strain has to be separated (and/or eliminated) or minimised in order to accurately account for the tensile force in the reinforcement. Hence in the experimental research program, it was necessary to incorporate strain gauges on both sides of the mesh/strand (i.e., top and bottom faces of the ribs) at the desired locations. The average of the strain readings obtained from these two strain gauges would give the approximate strain, primarily due to tension, across the geogrid at a specific location.

Since geogrids are usually made of polypropylene or polyethylene material, selecting an appropriate adhesive and coating material is also an important consideration. After extensive investigations with different types of adhesives on Tensar BX1200 (SS2) geogrid, the Loctite Super Bonder 495 general purpose instant adhesive used with M-Bond 200 adhesive as a catalyst was found to give reliable results. The experimental procedure adopted for installing strain gauges on geogrids is documented by Gnanendran (1987).

From results of tensile tests performed on geogrid samples of different width instrumented with multiple pairs of strain gauges installed at different locations across the reinforcement it was found that all the pairs of strain gauges do not exhibit the same tensile load versus strain relationship (Gnanendran, 1987). For a geogrid reinforcement, the strain measurement obtained in this manner at each location would indicate the local strain and it could be different from the global or average strain between the ends. Burger (1995) has studied the difference between local and global strain for this particular type of geogrid and reports a higher global strain of as much as 30% compared to the local strain. This difference can be attributed to a variety of factors including unequal cross sections at strain gauge locations arising from complicated geometric configuration of the geogrid (varying thickness and width of ribs at different sections), material non-linearity and effects of bending (varying curvature at different locations initially).

Since the strain gauges installed at different locations across a geogrid reinforcement would behave differently, it is difficult to interpret the tensile force in the geogrid from strain measurements, when it is used as reinforcement in a soil structure. Within the context of a laboratory research experiment, this problem could be overcome by calibrating each and every strain gauge independently in an appropriate tensile test prior and/or subsequent to its use as reinforcement. This approach, however, is not a realistic option when dealing with insitu instrumentation of prototype structures.

3. Model test facility

Foundations of bridge abutments are often supported on sloped fills or embankments and geosynthetic reinforcement may be used within the fill to enhance the performance of such structures. To study the behaviour of such foundations, a model test facility was established (Fig. 1). The load-displacement behaviour of the model footing located near the crest of a reinforced slope and the gradual development of stabilising force in the geogrid reinforcement was investigated using this model test

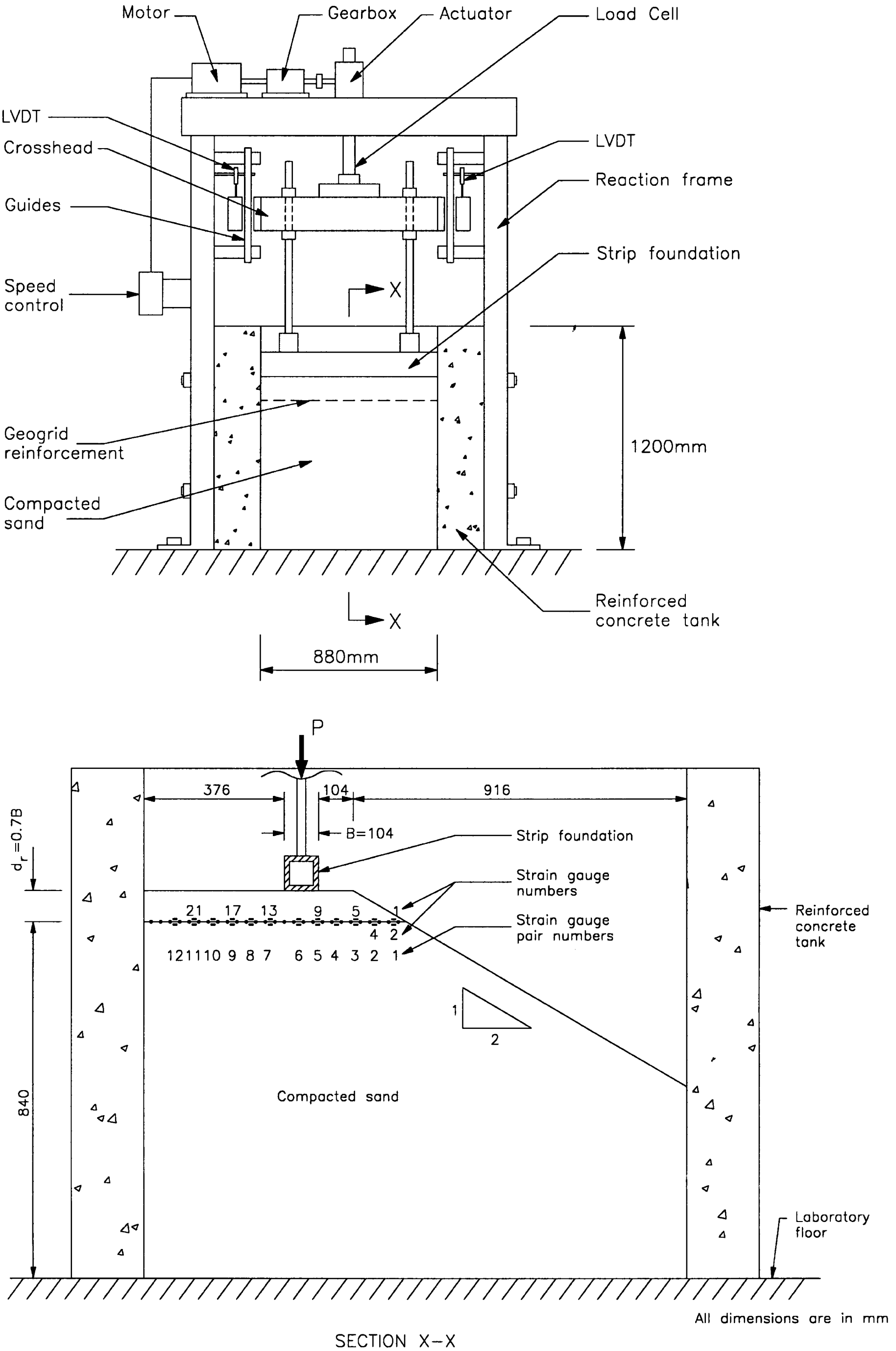

Fig. 1. Schematic of the model test facility and layout of instrumentation (modified after Selvadurai and Gnanendran, 1989).

facility. The slope angle, the positioning of the footing in relation to the crest and depth of placement of the geogrid reinforcement were chosen on the basis of model studies of bridge abutments founded on granular fills reported by Selvadurai and Gnanendran (1989).

The testing was carried out in a reinforced concrete tank measuring 1500 mm long, 880 mm wide and 1200 mm depth with the model strip foundation made of a steel box section measuring 104 mm wide and 870 mm long in plan. The sides of the test tank were fitted with polished stainless steel sheets to minimise end effects and the bottom of the model strip footing was made rough by spraying Ottawa sand onto a freshly placed layer of timber bonding glue. The footing was advanced at a constant rate with an automated motorised system and the resistance for settlement provided by the soil was measured with a load cell. The footing displacement was measured using a pair of LVDTs near the ends of the model strip footing (Fig. 1).

4. Strain gauge instrumentation of geogrid for model test

An extruded polypropylene biaxial Tensar BX1200 (SS2) geogrid was selected for use as reinforcement of the sloped fill in this laboratory investigation. Based on the studies reported by Selvadurai and Gnanendran (1989), the depth of embedment of the geogrid reinforcement (d_r) was selected to be $d_r = 0.7B$, where B is the width of footing, which was expected to give the maximum improvement in the ultimate bearing capacity of the sloped fill. Therefore an 870 mm wide by 740 mm long geogrid sample instrumented with 12 pairs of (Showa N11-FA-5-120-11) foil strain gauges along the centre line strand was used as reinforcement (see Section XX of Fig. 1 for strain gauge locations). To verify the reproducibility of the model test, two tests were carried out without strain gauge instrumentation on the geogrid prior to this test. As will be discussed later, the footing load displacement responses obtained from all three tests agreed well (Fig. 9). It is further noted that two additional series of tests were carried out to study the influence of depth of embedment and the type of geogrid reinforcement on the footing load-settlement behaviour of the reinforced sloped fill and those results also confirmed the reproducibility of the tests (Selvadurai and Gnanendran, 1989).

In view of the earlier discussion it was decided to calibrate each strain gauge independently as mounted in position on the geogrid specimen, which ultimately would be used as the slope reinforcement for the model test. A specially designed tensile test was carried out to calibrate the 12 pairs of strain gauges and the details of this testing is discussed below.

5. Calibration test for the strain gauges

As the tensile test specimen was quite large (740 mm long by 870 mm wide), it could not be accommodated in available standard tensile testing machines (especially the end clamps). Therefore, a new design for the end clamps and testing apparatus was

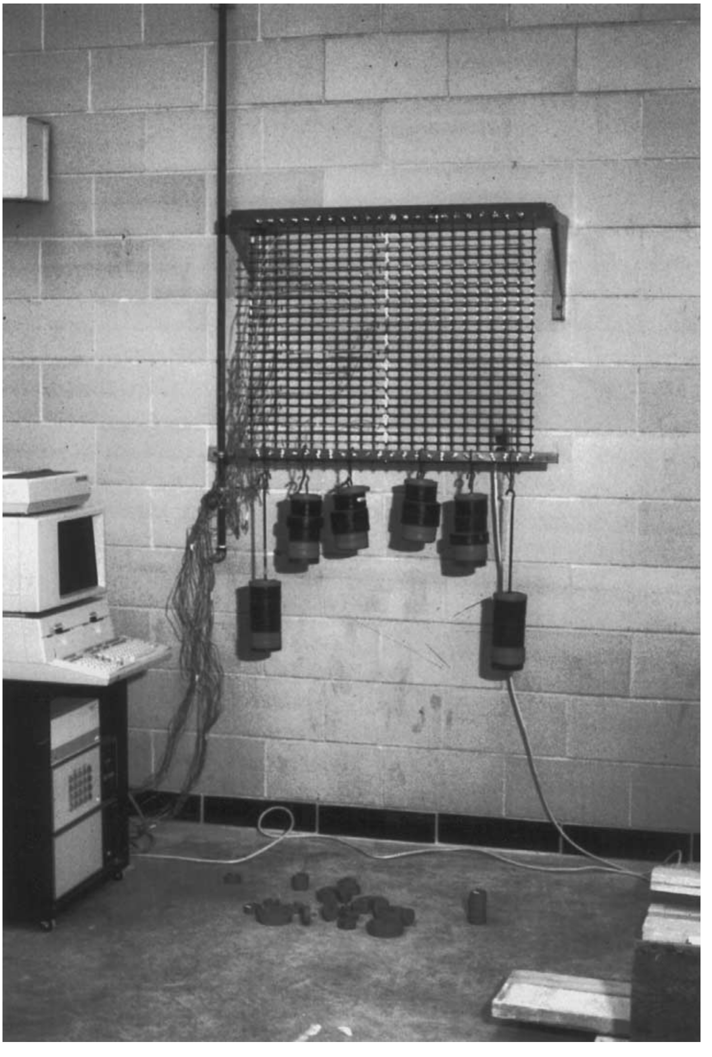

Fig. 2. View of the calibration tensile testing experimental set up.

necessary. Moreover, it was required that the end clamps should not damage the geogrid sample during the tensile test since it has to be used subsequently as reinforcement for the sloped fill test. The wide-width tensile test end clamp design suggested by ASTM (ASTM D 4595) for geosynthetics was found to be unsuitable because it could damage the specimen and/or the strain gauges installed near the ends. Similar difficulties were foreseen with other methods proposed in the literature for tensile tests on geosynthetics (e.g., McGown et al., 1984) and were therefore not adopted for this research. After considering all available alternatives, a basic but reliable method for performing the calibration tensile tests was developed.

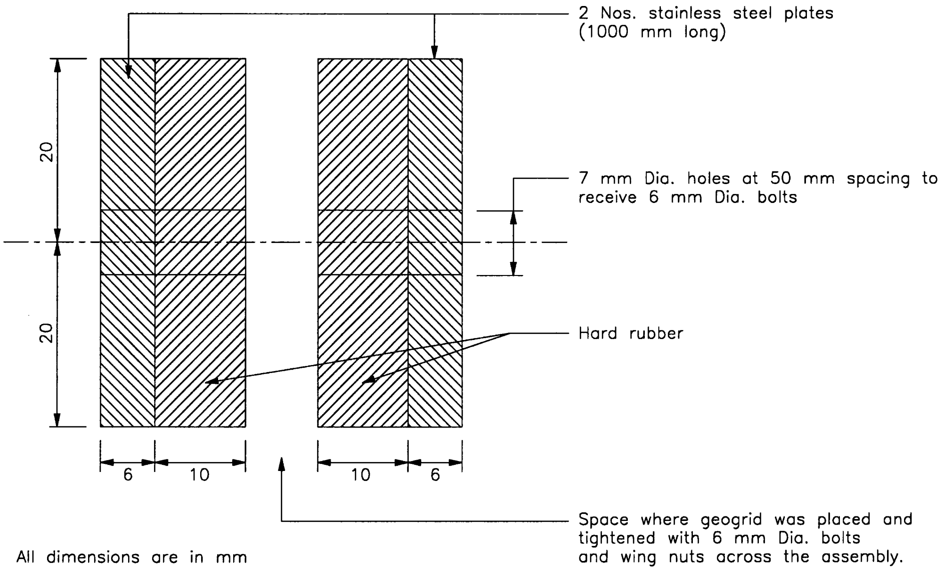

Fig. 3. Cross-sectional view of the calibration test end clamp.

A simple arrangement for clamping the geogrid sample without slip at its ends was employed for the calibration test. The structural support consisted of a pair of 1000 mm long, 40 mm wide and 6 mm thick stainless steel beams/plates. Hard rubber sheets were bonded to their flat sides (see Figs. 2 and 3). The geogrid test specimen was clamped between the two rubber bonded plates with the aid of 23 bolts spaced 50 mm apart passing through the grid openings. The clamping action was derived by tightening the wing nuts in a uniform fashion. Utmost care was taken to ensure that the geogrid does not come into contact with the clamping bolts. This arrangement is intended to ensure a uniform stress transfer from the end clamps to the geogrid through hard rubber and to avoid possible stress concentrations at the connections.

The six hangers were tied to the bottom clamp by means of wire wrapped around the clamp, again, avoiding direct contact with the geogrid. These hangers were placed symmetrically at approximately equal spacing. The tensile load was applied to the geogrid by placing weights on these hangers in an approximately uniform fashion (i.e., same increment of load on each hanger simultaneously) and in a step by step basis. The stainless steel plates clamped together at the bottom acted as a rigid beam to distribute the tensile force uniformly over the width of the geogrid. Prescribed loads were applied by placing weights on the hangers and the corresponding strain gauge readings were recorded with the use of a computerized data acquisition system. The calibration test was stopped at a tensile load level of about 1 kN in order to minimise the permanent deformation of the geogrid, which could influence its performance in subsequent model footing tests.

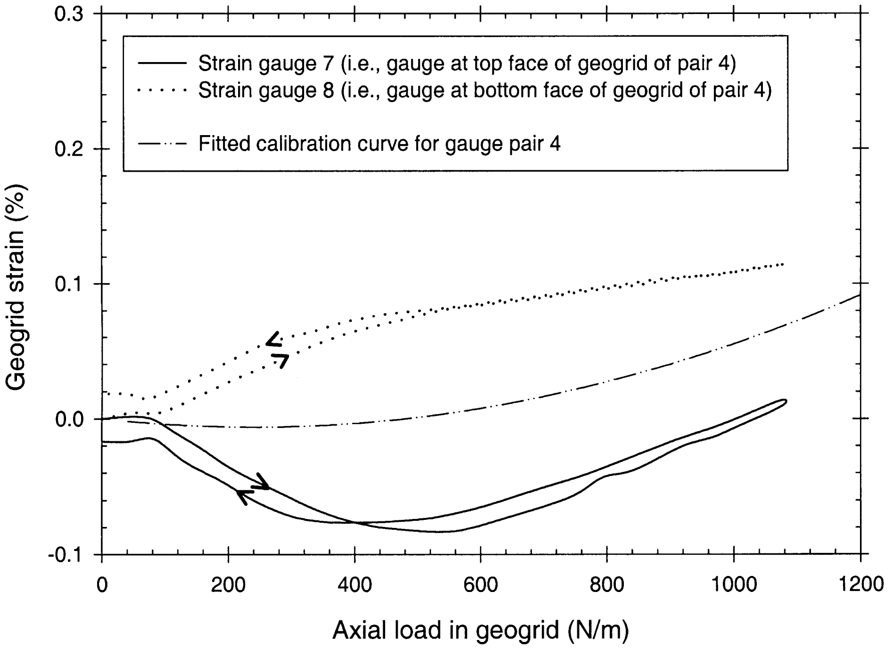

Fig. 4. Calibration curve for strain gauge pair 4 before footing load test on reinforced sloped fill.

The data acquisition system consisted of a HP 9836 computer and control units (HP 3497A Data Acquisition/Control Unit and HP 3498A Extender). For the calibration part of the experiment, the data acquisition system was programmed to collect the readings from the 24 strain gauges at specified load levels and to plot the individual calibration curves. Typical calibration curves obtained for selected pairs of strain gauges are shown in Figs. 4 and 5.

As discussed earlier, only the strain caused by tensile forces need to be measured. By considering the average strain of each pair of strain gauges the strain caused by changes in bending of the geogrid was minimised. The average strain versus tensile load for each pair of strain gauges was used as the calibration curve for subsequent assessment of the tensile force in the geogrid during model footing test.

The variations of average geogrid strain with tensile load displayed a nonlinear trend and it was found that a second-order polynomial curve fitting, performed via the least square method, was satisfactory. The calibration curves obtained in this way (i.e., one curve per pair of strain gauges) were the ones used for determining the force at different points across the geogrid, particularly when used as reinforcement for the sloped fill (Figs. 4 and 5). Upon completion of the calibration test, the end clamps were removed and the strain gauge instrumented geogrid test specimen was transferred carefully to the test tank for incorporation in the compacted sand in which the load tests were performed.

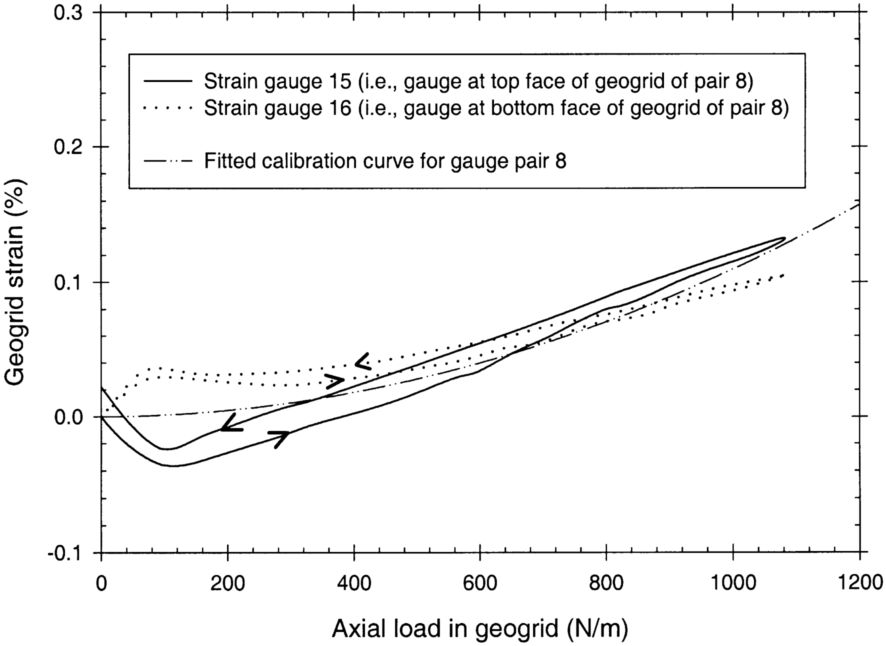

Fig. 5. Calibration curve for strain gauge pair 8 before footing load test on reinforced sloped fill.

6. Footing load test on sloped fill with instrumented geogrid as reinforcement

Mortar sand with particle size distribution shown in Fig. 6 was used as the fill material for the model testing. The moisture content of the sand was maintained between 4% and 5% during the testing. The sand was compacted manually, in 75 mm layers using a steel compactor weighing about 76 N, up to the required level in the test tank and the instrumented geogrid was placed in position. To maintain even density, each layer was compacted twice in a uniform fashion under the free fall of the compactor by approximately 150 mm. In all the sloped fill tests, bulk density of the mortar sand in its compacted state was kept constant at 17.6 kN/m^3. The friction angle of the soil was estimated to be approximately $\phi = 43^\circ$ from direct shear tests.

Since the strain gauges are very delicate and could be damaged by excessive bending, twisting or scratching, care was taken when transferring and placing the geogrid in position in the test tank (i.e., over the compacted fill). All the lead wires of the strain gauges were placed so that they would not interfere with the test. The remaining sand layers above the geogrid reinforcement was compacted up to the required elevation. The foundation assembly was then fixed in position and the slope excavated.

During the test, the footing was advanced at a constant rate of 0.02 mm/s and the induced load measured via a load cell. Settlement of the footing was measured with

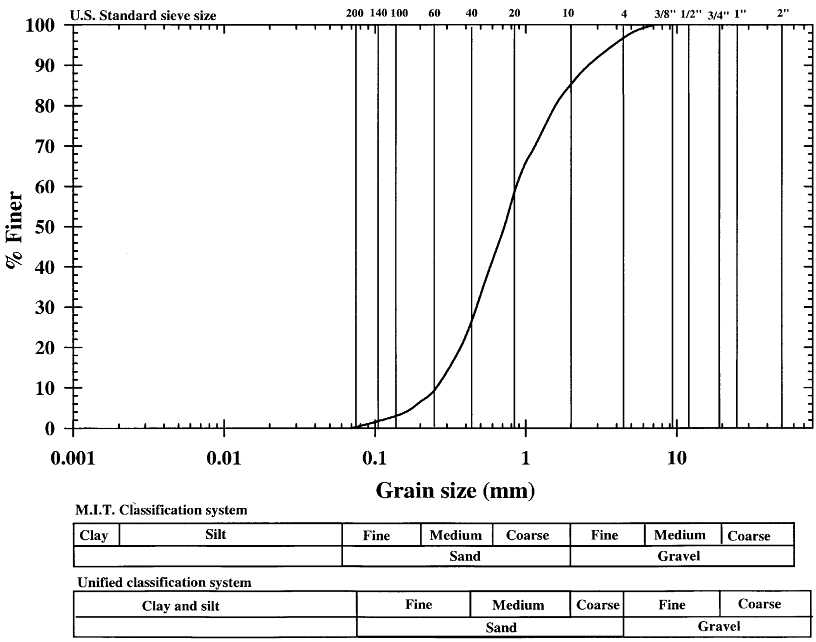

Fig. 6. Particle size distribution of the sandy fill.

the two LVDTs located near the ends of the model strip footing (Fig. 1). It was programmed to collect the readings from all 24 strain gauges, both LVDTs, and the load cell at 5-s intervals during an entire experiment. When the test was over, the foundation assembly was dismantled and the sand above the geogrid was carefully removed. The strain gauge instrumented geogrid was also removed carefully and a post-experiment calibration tensile test was conducted on the geogrid specimen.

7. Results and discussion of calibration tensile tests

Owing to effects which can most likely be attributed to bending of geogrid (i.e., flexural changes due to initial folding and rolling during manufacture/storage and subsequent straightening when using as reinforcement), the tensile load versus geogrid strain response obtained for the two strain gauges installed on opposite faces of the geogrid at each location were significantly different (Figs. 4 and 5). The strain gauges installed at different locations indicated significantly different tensile load versus geogrid strain relationship and they were highly nonlinear at low load levels, typically up to about 0.6 kN. It is further noted that most of the gauges recorded a small irreversible strain, maximum of about 0.02%, at the end of the calibration tensile test.

The average strain versus tensile load responses (hereafter referred as calibration curves) for the different pairs of gauges were of fairly consistent pattern. These calibration curves indicate a highly nonlinear behaviour at low tensile loads (e.g., up to about 0.5 kN for the pair of strain gauges 7 and 8 shown in Fig. 4) followed by a transition and a fairly linear behaviour at higher tensile loads. The stiffness of the geogrid based on average strain of the pair of strain gauges and applied tensile load ranged between 500 and 700 kN/m beyond the initial nonlinear region (e.g., the pair of Gauges 7 and 8 indicated a stiffness of about 500 kN/m for tensile load above 0.6 kN). The results of wide strip tensile tests performed on the same type of geogrid by Mylleville (1991) indicated a stiffness of approximately 690 kN/m for 0–0.5% strain, 580 kN/m for 0–1% strain and 450 kN/m for 0–2% strain. These values and those estimated from average strain from the pairs of gauges versus tensile load responses obtained in the current research agree well.

Examining the calibration test results of gauge pair 4 as a typical example, gauge 7 apparently being installed on the convex side of an initially curved/bent geogrid indicated a negative stiffness up to about 0.4 kN tensile load (Fig. 4). On the other hand, Gauge 8 apparently being installed on the concave side of an initially curved geogrid indicated an opposite response. Calibration plot for the pair of gauges shown in Fig. 5 also indicate a similar behaviour.

If one uses only one strain gauge per location, say for example either Gauge 7 or 8 at that particular location, and uses the nominal stiffness of the geogrid to interpret the force from the measured strain, the estimated geogrid force would be significantly different. This difference is particularly noticeable at low load levels (for up to about 0.5 kN for gauges 7 and 8). Even if one calibrates each gauge as installed in position from a tensile test, it would be extremely difficult, if not impossible, to interpret the geogrid force from individual strain measurements particularly due to the changes that will occur due to bending of the geogrid during its placement and the compaction of the granular material above it. However, if one installs strain gauges in pairs, as used in the experimental research reported in this paper, and uses the average strain versus tensile load responses obtained from the calibration tensile tests, it would enhance the accuracy and reliability of the relationship between the strain measurement and the estimation of the geogrid tensile force.

The calibration tensile test was repeated after the sloped fill footing load test on the strain gauge instrumented geogrid reinforcement in order to verify the effect of any irreversible deformations and hysteresis of geogrid on the experimental results. Another set of calibration curves was obtained for the 12 pairs of strain gauges. Typical calibration curves obtained for selected pairs of strain gauges are shown in Figs. 7 and 8. Also shown in these figures is the average strain versus tensile load for each pair of strain gauges.

These calibration plots indicate an almost linear average strain versus tensile force relationship for the geogrid at all load levels. Consequently, for this calibration test conducted after the sloped fill footing load test, linear estimates for the average strain versus tensile load (as determined via the least square method) were found to be satisfactory. The stiffness estimated from these calibration plots ranged from 550 to 700 kN/m (e.g., stiffness of about 590 kN/m from the pair of gauges 7 and 8 — see Fig. 7). Again, this stiffness range also agrees well with that obtained from wide strip tensile test results reported by Mylleville (1991).

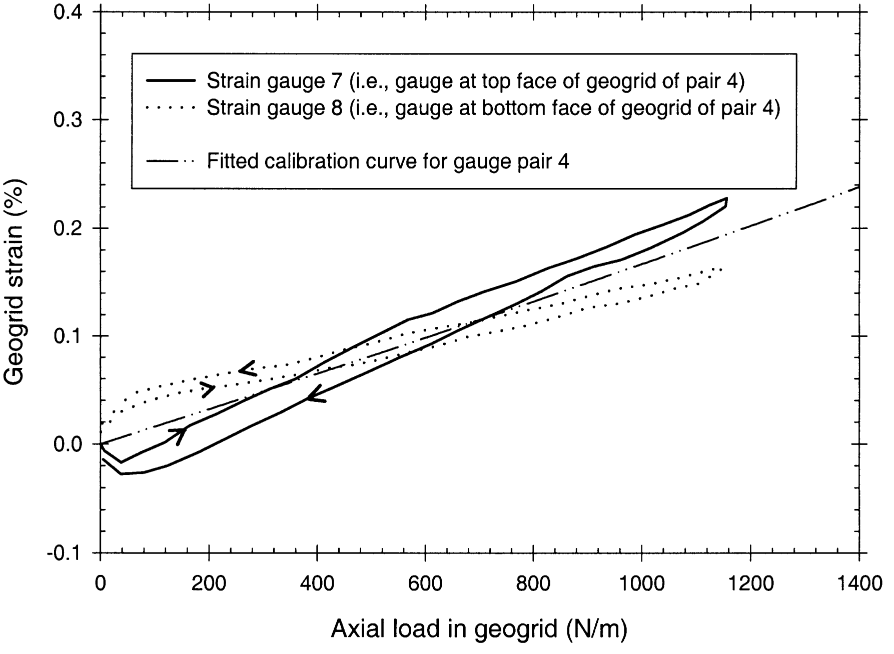

Fig. 7. Calibration curve for strain gauge pair 4 after footing load test on reinforced sloped fill.

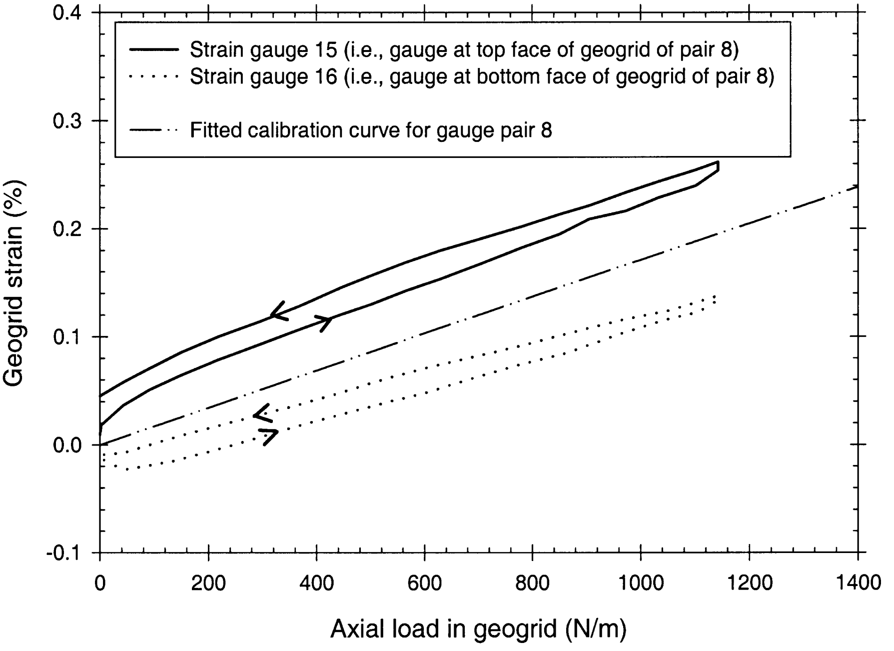

Fig. 8. Calibration curve for strain gauge pair 8 after footing load test on reinforced sloped fill.

It is further noted that there was not any sign of de-bonding of strain gauges occurring during the entire testing programme. This is consistent with the finding of the earlier investigation where cyclic tensile loading tests were carried out to verify the reliability of strain gauge installation method for the particular type of geogrid (Gnanendran, 1987).

Comparing the calibration plots obtained before and after the sloped fill footing load test for each pair of strain gauges (e.g., Figs. 4 and 7 for gauge pair 4), a significant change in the tensile force — strain relationship of the geogrid is evident. The initially nonlinear form followed by linear tensile load versus average-strain relationship observed during the calibration tensile test prior to the sloped fill footing load test has changed into a predominantly linear relationship for the entire tensile load range. This is likely due to the strain hardening effects of the geogrid caused by the loading during the initial calibration test and the subsequent sloped-fill footing load test. However, the range of stiffness of the geogrid as indicated from the calibration test prior to the sloped fill footing load test (for tensile load above 0.6 kN) and that after the sloped fill test (for all load levels) were almost the same. Considering the fact that the particular geogrid being made of polypropylene material with visco-elastic characteristics, the above difference between the two calibration responses is not significant.

This strain-hardening type of behaviour of the geogrid suggest that the tensile force — strain relationship obtained from the calibration test performed after the sloped fill test would represent the behaviour of the geogrid reinforcement more closely than that obtained from calibration test performed prior to the sloped fill footing load test. However, the geogrid was loaded only up to 1 kN tensile load (i.e., to a largest tensile strain of less than 1600 microstrain) during the calibration test prior to the footing load test. Therefore, the actual strain — tensile force relationship of the geogrid when it was used as reinforcement for the sloped fill would be expected to lie in between the corresponding responses obtained from the two calibration tensile tests (i.e., both before and after the sloped fill test for each pair of gauges).

8. Results of footing load test on reinforced sloped fill and discussion

As discussed previously, the footing load test on the geogrid reinforced sloped fill was initially performed twice without strain gauge instrumentation of the geogrid to verify whether the overall behaviour could be reproduced. The load-displacement behaviour obtained from both tests agreed well, confirming that the test results could be reproduced and were therefore reliable (Fig. 9) under these conditions of testing. The load-displacement behaviour of the footing obtained from the test with strain gauge instrumentation also agreed well with the two preliminary tests. The results further confirm that the presence of strain gauge instrumentation did not exert any influence on the overall load-displacement response of the footing.

Based on the strain measurements from the sloped fill footing load test with instrumented geogrid as reinforcement, the geogrid tensile force at the location of each pair of strain gauges was evaluated at different foundation load levels. Both sets of calibration curves (i.e., one set each obtained from the tensile tests performed before

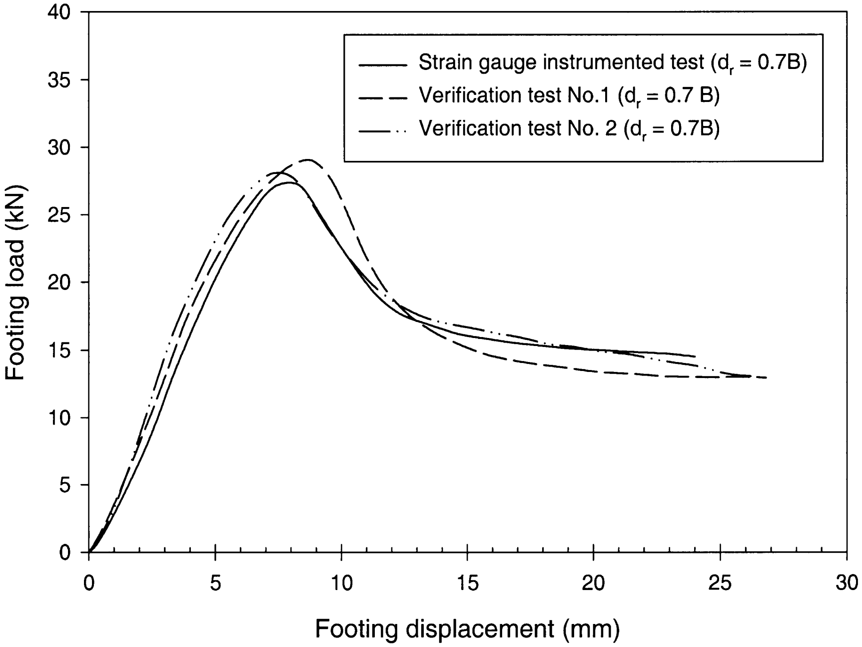

Fig. 9. Load-displacement relationship for the footing located on reinforced sloped fill.

and after the reinforced sloped fill footing load test) were used separately to ascertain the tensile force at different locations along the geogrid. Typical tensile force distributions along the geogrid reinforcement obtained when the foundation load was at 40% of its ultimate (i.e., corresponding to a factor of safety of 2.5) and at its ultimate (i.e., 100% of the ultimate) foundation load capacity are shown in Figs. 10 and 11, respectively. For ease of comparison, the tensile force in the geogrid is expressed as a percentage of the ultimate (i.e., maximum) foundation load. The distances are measured from the centre line of the foundation and normalised with respect to the width of foundation, B. The distances from the centre line of the foundation towards the crest of the slope are shown as positive and those in the opposite direction are considered to be negative.

These results indicate that the tensile force across the geogrid varies from zero at the ends and increases up to a maximum value at a point close to the foundation. Fig. 11 shows that the length of geogrid reinforcement was more than sufficient to allow full load transfer to take place between the geogrid reinforcement and soil. This is due to the fact that the pair of strain gauges placed at approximately $0.75B$ from the end of the geogrid reinforcement (i.e., relative position $= -3.3B$) indicated zero tensile force at their location throughout the footing load test.

When the foundation load was at 40% of the ultimate, the tensile force at all locations in the geogrid obtained using the calibration curves after the sloped fill test

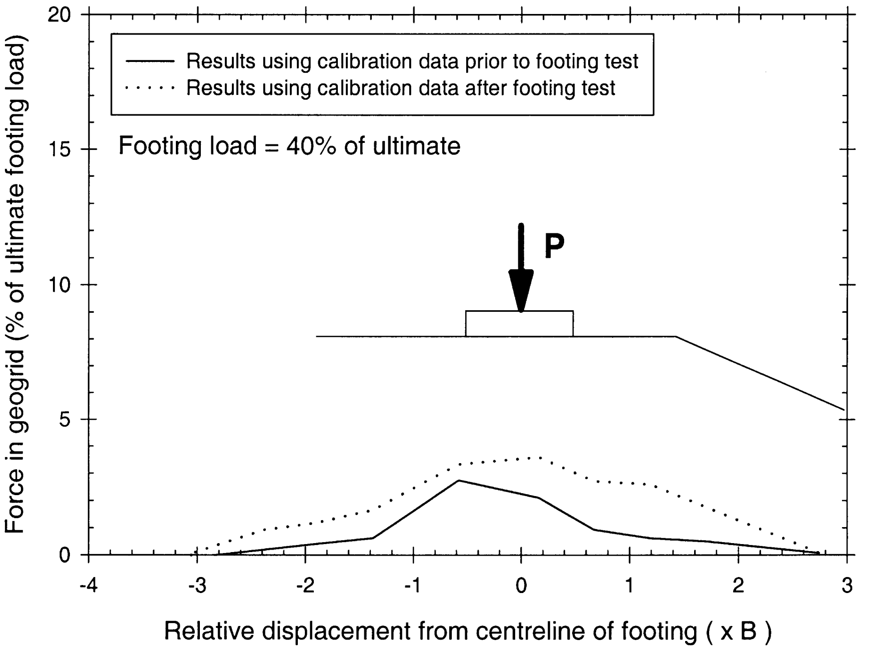

Fig. 10. Variation of the tensile force across the geogrid reinforcement when the footing load was 40% of ultimate.

were higher than those indicated by the calibration curves before sloped fill footing load test (Fig. 10). However, when the foundation load was at its ultimate, the maximum tensile force in the geogrid obtained using the calibration curves from the tensile test before the sloped fill footing load test was higher than that obtained using the calibration after the footing load test (Fig. 11). These results further indicate that the largest tensile force developed in the geogrid reinforcement is only about 10.5% of the foundation load.

The plot of the maximum tensile force across the geogrid versus the foundation pressure is shown in Fig. 12. Here again, the plots obtained by using the calibration curves from the calibration tensile tests performed before and after the reinforced slope fill structure test are shown separately. These plots indicate that the applied foundation pressure and the maximum tensile force developed in the layer of geogrid reinforcement are not linearly related. By using a least squares method, empirical relationships were obtained between the maximum tensile force developed in the geogrid reinforcement, $T_{\max}$ (kN/m width), and the applied foundation pressure, q_f (kN/m^2). Using the calibration curves from the tensile test performed before the sloped fill footing load test

$$T_{\max} = 2.773 \times 10^{-3} q_f + 3.4084 \times 10^{-5} q_f^2. \tag{1}$$

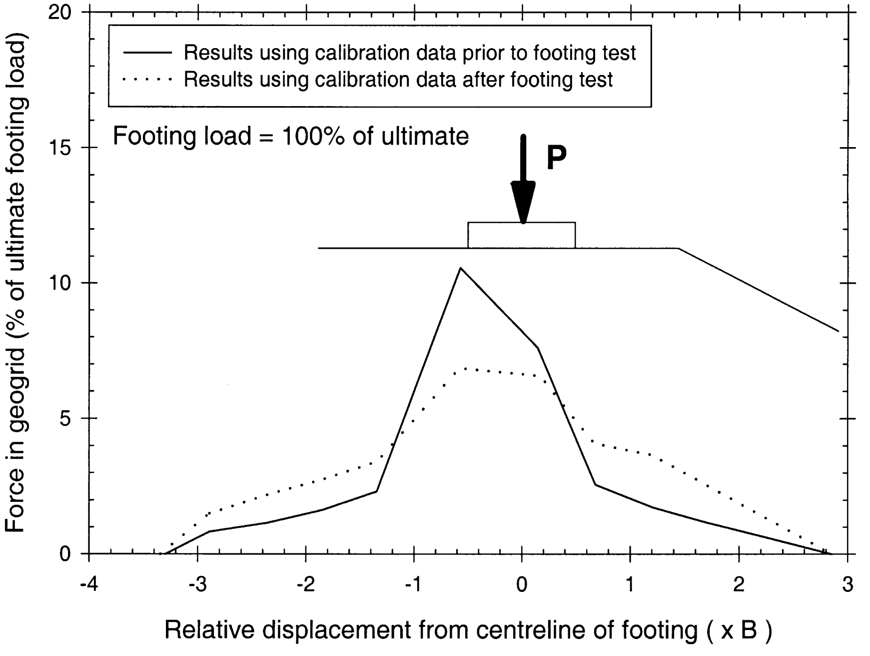

Fig. 11. Variation of the tensile force across the geogrid reinforcement at ultimate footing load.

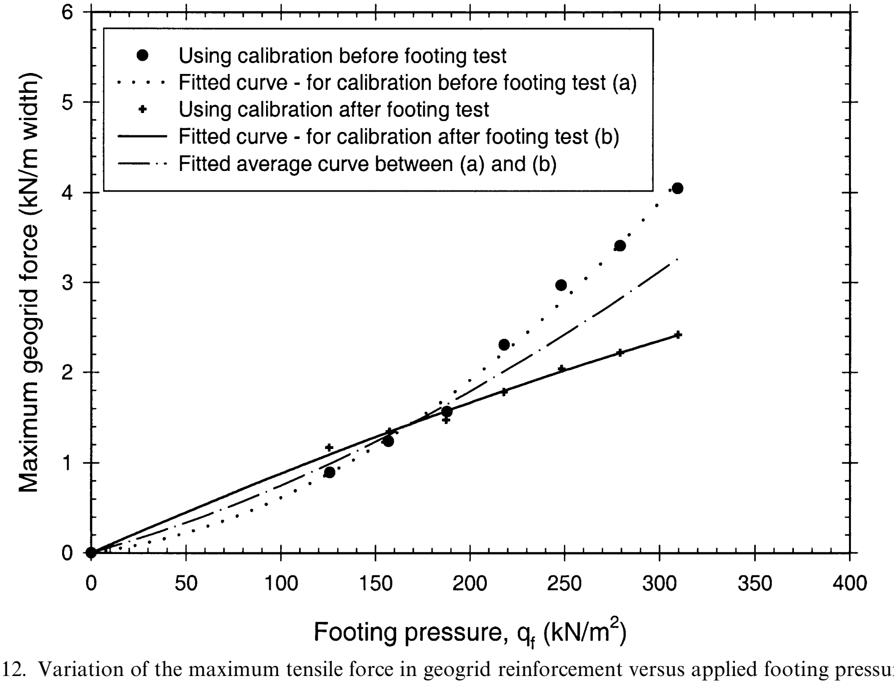

Fig. 12. Variation of the maximum tensile force in geogrid reinforcement versus applied footing pressure.

Similarly, based on the calibration curves from the tensile test performed after the sloped fill footing load test,

$$T_{\max} = 9.3345 \times 10^{-3} q_{\mathrm{f}} - 4.9633 \times 10^{-6} q_{\mathrm{f}}^2. \tag{2}$$

As discussed previously, the actual strain - tensile force relationship for the geogrid when used as sloped fill reinforcement was expected to be in between the results of the calibration tests performed before and after the sloped fill test. Therefore, the relationship between the maximum geogrid force and the foundation pressure may be expressed by the average curve between those obtained using the two calibration test results (Fig. 12) and given by the equation:

$$T_{\max} = 6.054 \times 10^{-3} q_{\mathrm{f}} + 1.456 \times 10^{-5} q_{\mathrm{f}}^2. \tag{3}$$

It is noted, however, that these relationships need to be verified with instrumented full-scale structures before application in real design problems.

9. Summary and conclusions

Performance of the geosynthetic in a reinforced soil structure is an important consideration for design and is usually assessed by monitoring the developed strain with electrical resistance strain gauges. Geosynthetic reinforcement contributes to the stability of soil structures primarily due to their tensile stiffness but changes in local strain measurements could occur due to the effects of bending as well. Therefore, the interpretation of the actual force developed in the geosynthetic reinforcement (i.e., the stabilising force provided by the reinforcement to the soil structure) on the basis of measured strain in the reinforcing element requires careful consideration and forms the basis of this paper.

A small-scale laboratory study was conducted to evaluate the stabilising force provided by a geogrid reinforcement layer to the sloped fill subjected to footing load. Electrical strain gauges were installed in pairs (i.e., on top and bottom faces of the geogrid) at each location across the geogrid reinforcement to account for the changes in geogrid strain due to the effects of bending. Since each gauge installed at different locations across a geogrid sample would behave differently, a reliable but simple method to perform tensile tests on a wide (i.e., on the entire 870 mm) sample of geogrid was developed for calibrating these gauges as installed in position. Details of this tensile testing method and the calibration results are presented in the paper.

This study indicates that if only one strain gauge per location across the reinforcement is used, the estimated geogrid force, on the basis of measured strain and nominal stiffness, would be in error especially at low load levels. Even if each gauge is calibrated as installed in position from a tensile test, it would not be possible to interpret the geogrid force from individual strain measurements accurately for these low load levels. Therefore, the use of single strain gauge at each location for the interpretation of geogrid loads is not advocated. This study presents the results of an experimental research program where strain gauges are installed in pairs on either face of the geogrid, in order to interpret the load development more accurately.

Calibrating the strain gauges as installed in position with a suitable tensile test would further enhance the accuracy of the estimation of the geogrid force. Such an approach, however, be restricted to only laboratory investigations.

Gradual development of the stabilising force along the length of the geogrid reinforcement, with increasing foundation load, was evaluated for a particular geometric configuration of the sloped fill and depth of embedment of the geogrid reinforcement ($d_r = 0.7B$). The variation of the maximum tensile force developed in the geogrid with the applied foundation pressure exhibits a nonlinear trend and this variation can be described by a second order polynomial relationship in terms of the average foundation pressure (i.e., Eq. (3)). The experimental study further illustrates that the largest tensile force developed in the geogrid reinforcement is approximately 10.5% of the maximum foundation load applied on the sloped fill.

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