An experimental study of a footing located on a sloped fill: influence of a soil reinforcement layer

A. P. S. SELVADURAI AND C. T. GNANENDRAN

Department of Civil Engineering, Carleton University, Ottawa, Ont., Canada K1S 5B6

Received June 2, 1988

Accepted February 22, 1989

This paper summarizes the results of a series of experimental investigations conducted to determine the manner in which the performance of a footing located at the crest of a sloped fill can be influenced by the presence of a reinforcing layer within the body of the fill. The results of these investigations indicate that both the load–settlement behaviour and the ultimate capacity of the footing can be enhanced by the presence of the reinforcing layer and that such efficiencies are derived for specific depths of embedment of the reinforcing layer.

Key words: footings, reinforced slopes, ultimate capacity, load–displacement behaviour, failure modes.

Cet article résume les résultats d'une série d'études expérimentales réalisées dans le but de déterminer de quelle façon la performance d'une semelle localisée sur la crête du talus d'un remblai peut être influencée par la présence d'une couche d'armature dans le corps du remblai. Les résultats indiquent que tant le comportement charge–tassement que la capacité portante ultime de la semelle peuvent être améliorés par la présence de la couche armée, et que de telles efficacités peuvent être déduites des profondeurs spécifiques d'enchâssement de la couche d'armature.

Mots clés : semelles, talus armés, portance ultime, comportement charge–déformation, modes de rupture.

[Traduit par la revue]

Can. Geotech. J. **26**, 467–473 (1989)

Introduction

Foundations located on sloped embankments are used quite extensively as supports for bridge abutments. The estimation of the ultimate load capacity and the load–settlement behaviour of such foundations is important to the safe and efficient design of such foundations (see, e.g., Meyerhof 1963; Winterkorn and Fang 1975; Shields *et al.* 1977; Devata 1984). The positioning of an abutment in relation to the edge of an embankment fill has implications not only on the safety of the bridge abutment but also on the economic efficiency of the overall design of the bridge structure. For these reasons several procedures have been proposed to enhance the performance of bridge foundations located in embankment fills. These range from the incorporation of deep deposits of granular fill material to the incorporation of piles to supplement the load-carrying capacity of the foundation.

Recent initiatives at the Ministry of Transportation of Ontario have suggested the incorporation of soil-reinforcing techniques to enhance the load-carrying capacity and settlement behaviour of abutment foundations. In particular, the reinforcing techniques concentrate on the use of geogrids for improving the performance (i.e., the load-carrying capacity and settlement) of the abutment fill. Geogrids are essentially synthetic reinforcing mesh structures used, to varying degrees of success, in soil improvement associated with earth slopes, foundations for roads and aircraft landing areas, pavements, earth retaining structures, stabilization of slopes, etc. (see, e.g., Ingold 1982; Jones 1985; Koerner 1986). Geogrids have been used to enhance the bearing capacity of soils. Examples of such applications are given by Binquet and Lee (1975*a*, *b*), Bassett and Last (1978), Akinmusuru and Akinbolade (1981), Akinmusuru *et al.* (1982), Fragaszy and Lawton (1984), and Chang (1985). In these investigations it is shown that both the ultimate capacity of the footing and its settlement characteristics can be improved by the incorporation of geogrids within the body of the granular soil. References to further applications are given in the articles cited previously and in articles by Jewell *et al.* (1984*a*, *b*).

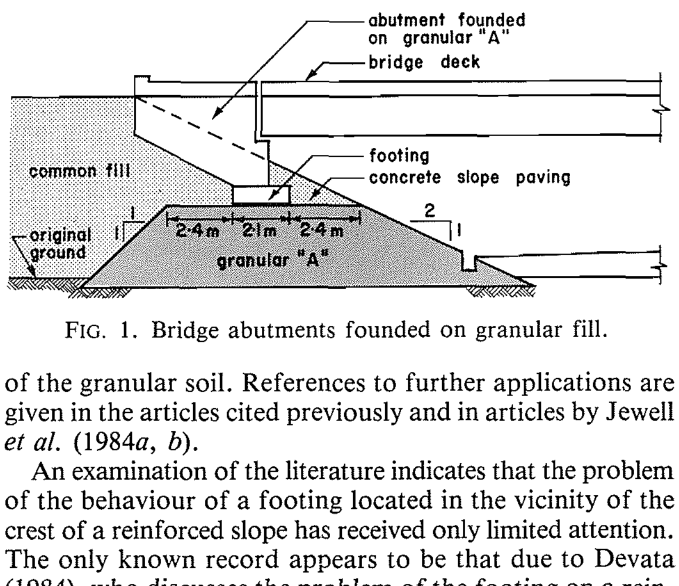

FIG. 1. Bridge abutments founded on granular fill.

An examination of the literature indicates that the problem of the behaviour of a footing located in the vicinity of the crest of a reinforced slope has received only limited attention. The only known record appears to be that due to Devata (1984), who discusses the problem of the footing on a reinforced slope in reference to an application to the study of a bridge abutment (Fig. 1). The scope of the investigation was particular to the specific structure under examination. In view of the potential importance of the problem to bridge foundation design, it is instructive to investigate further some salient features that influence the performance of the footing located in the vicinity of a reinforced slope.

This paper primarily deals with an experimental modelling and investigation of the reinforcing efficiency of the geogrid in terms of its location, depth of embedment, and to a limited extent the type of geogrid. A complete experimental modelling of the problem should take into consideration a variety of factors including (i) inclination of the slope, (ii) location of the footing from the crest of the slope, (iii) spatial location of the geogrid, (iv) type of geogrid in terms of its aperture size, strength, elasticity, and directionality, (v) nature of loading of the foundation, (vi) depth

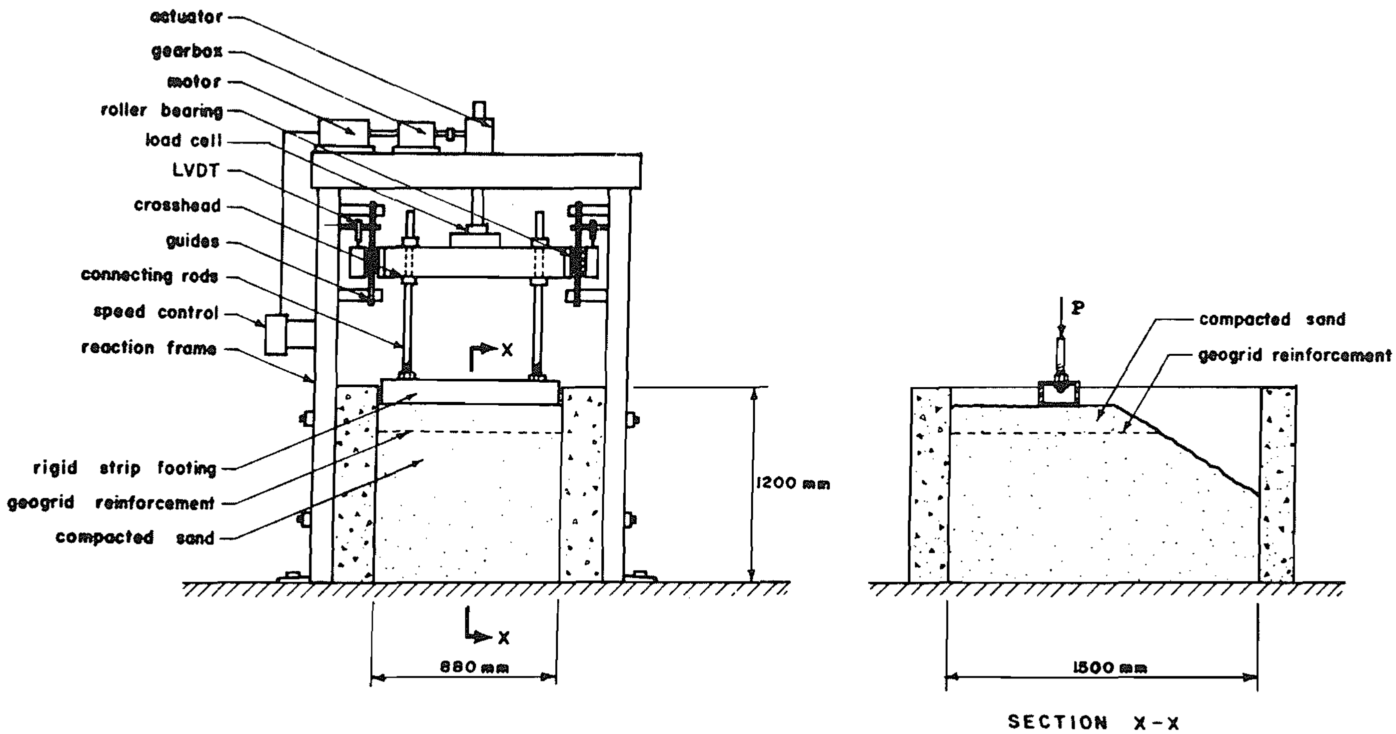

FIG. 2. A schematic view of the test facility.

and type of fill, and (vii) three-dimensional nature of the footing geometry. Clearly, the complete treatment of all of the above variables, within the context of an experimental research programme, entails a large amount of work. For this reason it was decided to focus attention on a reduced experimental research programme in which salient features of the problem were given first consideration. The paper discusses the experimental procedures that were designed particularly to examine the influence of the depth of embedment of a geogrid on the load–displacement performance of a footing located near the crest of a slope. The position of the footing from the edge of the slope is held constant in order to evaluate the influence of the depth of location. The positioning of the footing approximately corresponds to the footing location suggested by existing design guides (Devata 1984). The paper describes the results of the experimental programme and illustrates that within the context of the laboratory investigations, optimum locations can be achieved for the placement of geogrids within sloped fill embankments utilized as approach fill structures.

Experimental programme

The model tests were conducted in a reinforced concrete test tank with the following dimensions: 1500 mm in length, 880 mm in width, and 1200 mm in depth. The rigid strip foundation is modelled by a steel box section measuring 104 mm × 870 mm in plan area. A schematic view of the test facility is shown in Fig. 2. The longitudinal sides of the tank were fitted with highly polished stainless steel sheets to reduce the friction between the soil and the sides of the test tank and to induce a state near plane strain in the tested soil mass. The constant rate of movement of the footing is controlled by a worm gear - actuator assembly driven by an electric motor. The foundation is attached to a crosshead capable of moving vertically along roller bearings attached to the reaction frame. The reaction frame is anchored to the reinforced concrete floor, independent of the test container. As the crosshead moves at a constant rate, the foundation on the sloped fill moves vertically downwards as a rigid body at a constant rate. The induced foundation load is measured by the load cell incorporated in the actuator assembly (Fig. 2). The two linear voltage displacement transducers (LVDT's) installed symmetrically between the crosshead and the reaction frame, as shown in Fig. 2, measure the vertical displacements (i.e., settlement) of the foundation. The loading motor is connected to the load control unit. The load cell and LVDT's were connected to a HP 3421 data acquisition control unit, which was in turn connected to a HP 9836 desk top computer. The rate of the vertical movement of the foundation was kept to a constant value of 0.02 mm/s for the entire investigation. The data acquisition system was used to collect the foundation load (P) - settlement (Δ) readings at preprogrammed intervals of time during the entire experimental phase. The software is written in such a way that it is possible to monitor the load–displacement behaviour of the foundation during the progress of an experiment.

A mortar sand was used as fill material for the entire experimental investigation. The effective diameter, D_{10}, was found to be 0.27 mm, the coefficient of uniformity, C_u, was calculated to be 3.0 and the curvature coefficient, C_c, was found to be 0.95. Using the Unified Soil Classification system, the material was determined to be SP (poorly graded sand, gravelly sand with little or no fines). The moisture content of the mortar sand was maintained between 4 and 5% during the entire testing programme. In all experiments, the bulk density of the mortar sand in its compacted state was maintained at 17.6 kN/m^3. The approximate angle of internal friction for the soil is estimated at ϕ = 43°.

The sand was manually compacted in 75 mm layers with a steel compactor weighing about 76 N. The compactor was

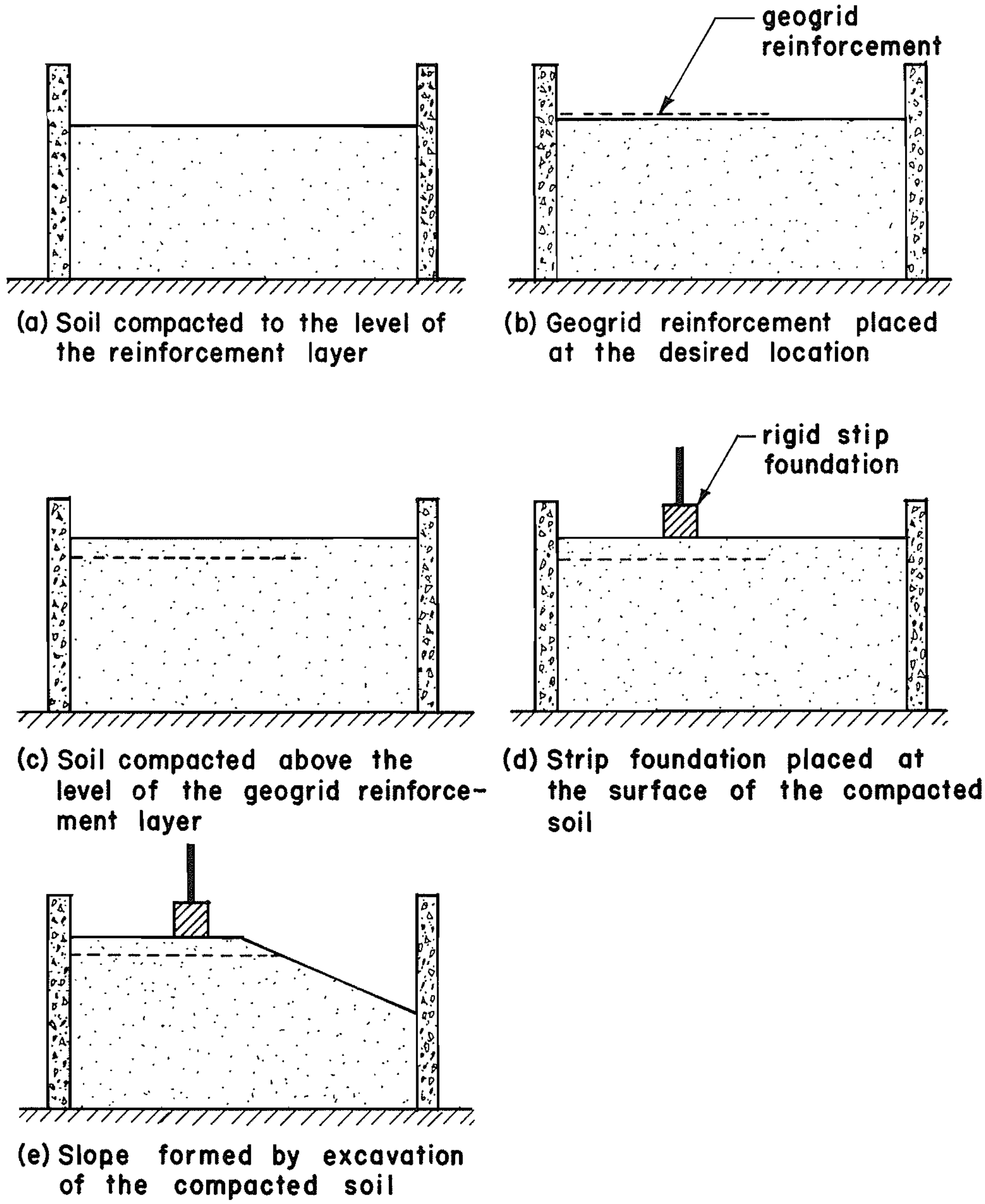

FIG. 3. Procedure for the installation of the geogrid and the formation of the slope.

lifted approximately 150 mm and allowed to free fall on the sand surface. Each layer was compacted twice to maintain an even density. The compaction operation was performed carefully to ensure the use of approximately the same specific compaction energy (i.e., compaction energy per unit volume) for each test. The geogrid reinforcement was placed on a compacted level surface at the required elevation. The length of the reinforcement for each depth was such that reinforcement was present from the boundary of the tank to the sloped fill surface. After the soil was compacted to the required level, with geogrid reinforcement buried at the required depth, the strip foundation was assembled in position. The compacted fill was then excavated to form the slope of 1V:2H. The stages in the development of the experimental technique are shown in Fig. 3. The final dimensions of the typical test configuration are shown in Fig. 4. (For details, see Gnanendran (1987).)

Upon completion of the test, the approximate location of the failure surface was determined by using probe techniques. In this method a small-diameter (3 mm) brass rod with a pointed end is inserted manually into the fill region.

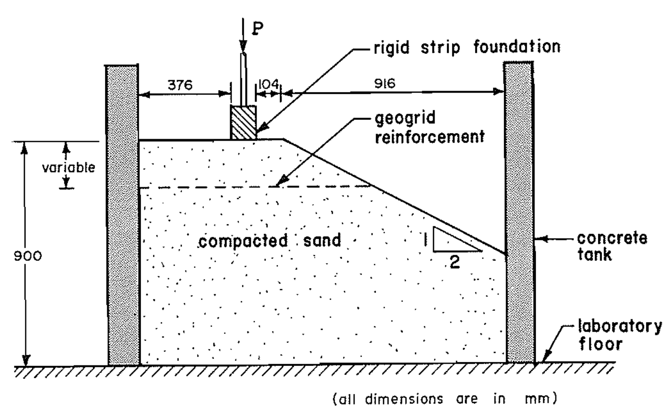

FIG. 4. Final configuration of the rigid footing on a reinforced slope.

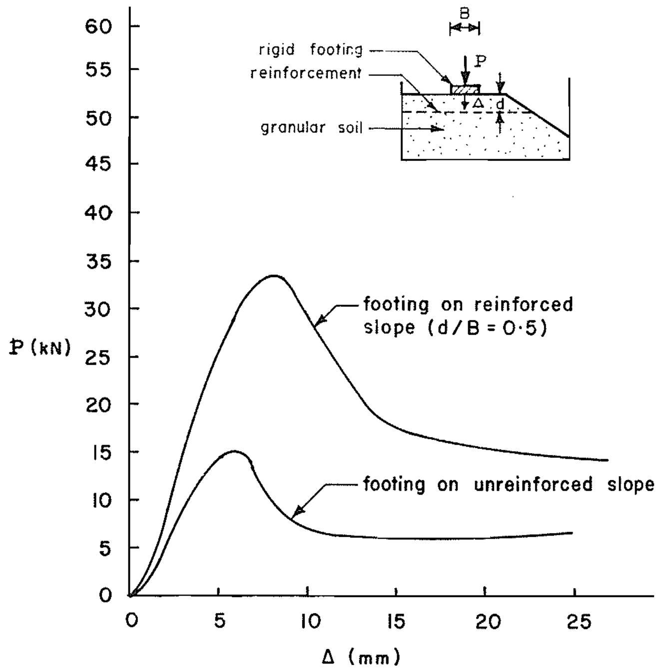

FIG. 5. Load–displacement relationships for rigid footing located on reinforced and unreinforced slopes.

As the tip encounters the failure zone a change in the penetration resistance is encountered. The rod experiences a reduction in the penetration resistance in the failure zone and reestablishes an increase in the resistance in the intact material region. By continuing this probing technique manually at several points on the sloped fill, an approximate failure surface path was established for each test.

Experimental results

In this section we shall summarize the results of the experimental investigations focusing on the performance of footings resting on both reinforced and unreinforced slopes. The initial series of experiments dealt with the evaluation of the load–displacement behaviour of the footing resting on an unreinforced slope. The results derived for the load–displacement behaviour in the case of unreinforced slopes formed the basis for investigating the effectiveness of the geogrid reinforcement. Figure 5 illustrates the typical load–displacement curves obtained for footings located on reinforced and unreinforced slopes. In the first series of experiments involving reinforced slopes the SS2 geogrid (Netlon, Ltd. 1982; Tensar Corporation 1986) was utilized. Also, when the footings were located on reinforced slopes, the depth of embedment location was changed to ascertain the influence of the location of the geogrid on the load–displacement response. Three tests were conducted for each specific value of the depth of embedment of the reinforcement. Altogether, six depths of embedment of the reinforcement were considered in the experimental programme.

Two types of information were pertinent to examining the efficiency of the geogrid in enhancing the performance of the footing on a slope. The first deals with the settlement behaviour of the footing and the second deals with its ultimate bearing capacity. The results of the experimental investigations can be presented in a variety of ways. Since the primary objective of the experimental research focuses on the evaluation of the efficiency of the reinforcement, it is convenient to present results for the reinforced system (for either the settlement or ultimate capacity) that are normalized with respect to the corresponding results derived for the footing on an unreinforced slope. We first examine the stiffness of the soil–footing system. In this case the term stiffness is defined as the slope of the load–displacement curve in the initial nearly linear stages of the curve. It is observed (see Fig. 5) that this curve usually exhibits a nonlinear initial region primarily resulting from any bedding errors associated with the contact between the soil and the footing surface. Once these bedding errors are accounted for it is possible to derive a stiffness relationship for the footing. Figure 6 illustrates the manner in which the stiffness ratio S_R defined by

$$[1] \quad S_R = \frac{[dP/d\Delta]^{\text{Reinforced}}_{\Delta\to 0}}{[dP/d\Delta]^{\text{Unreinforced}}_{\Delta\to 0}} = S_R(d/B)$$

is influenced by the depth of embedment d of the geogrid layer. It is evident that as the depth of embedment increases an optimum location of the geogrid, in terms of its efficiency in minimizing the settlements of the footing, can be established. The results presented in Fig. 6 indicate the average value and the range of values derived for the set of three tests. The solid curve shows a polynomial that is fitted to the average value of the data. This curve can be represented by the equation

$$[2] \quad S_R \approx 1 + \frac{d}{B} + \frac{3}{4}\left(\frac{d}{B}\right)^2 - \frac{7}{3}\left(\frac{d}{B}\right)^3 + \left(\frac{d}{B}\right)^4$$

The second aspect of the experimental results deals with the ultimate load capacity of the footing on a reinforced slope. Here again, it is convenient to define an ultimate load capacity ratio Q_R given by

$$[3] \quad Q_R = \frac{[P_{\max}]^{\text{Reinforced}}}{[P_{\max}]^{\text{Unreinforced}}} = Q_R(d/B)$$

Figure 7 illustrates the manner in which the value of Q_R is influenced by the depth of location of the geogrid. Again, it is evident that there is an optimum value of the depth of embedment of the geogrid for which maximum benefit is derived for the ultimate load capacity. The variation of Q_R with depth of embedment can be represented by the equation

$$[4] \quad Q_R \approx 1 - \frac{4}{10}\left(\frac{d}{B}\right) + \frac{22}{3}\left(\frac{d}{B}\right)^2 - \frac{19}{2}\left(\frac{d}{B}\right)^3 + \frac{13}{4}\left(\frac{d}{B}\right)^4$$

At low depths of embedment ($(d/B)<0.5$), the increase in the load-carrying capacity is primarily due to improved load redistribution provided by the geogrid. At large depths of embedment ($(d/B)>1.5$), the presence of the geogrid reinforcement does not lead to a significant improvement in the load-carrying capacity. The location of the failure surface was also estimated at the termination of each experiment. The influence of the depth of embedment of the geogrid reinforcement on the failure path is summarized in Fig. 8. These observations indicate that the failure paths exhibit a similar pattern when $d/B<1$. When $d/B>1$, the failure path is significantly altered and the failure occurs at the soil–geogrid interface. For geogrid depths where $d/B>1$, it would appear that the plane of the geogrid acts as a plane of weakness (i.e., the plane of failure occurs just above the geogrid). The beneficial effects of the geogrid strength and the soil con-

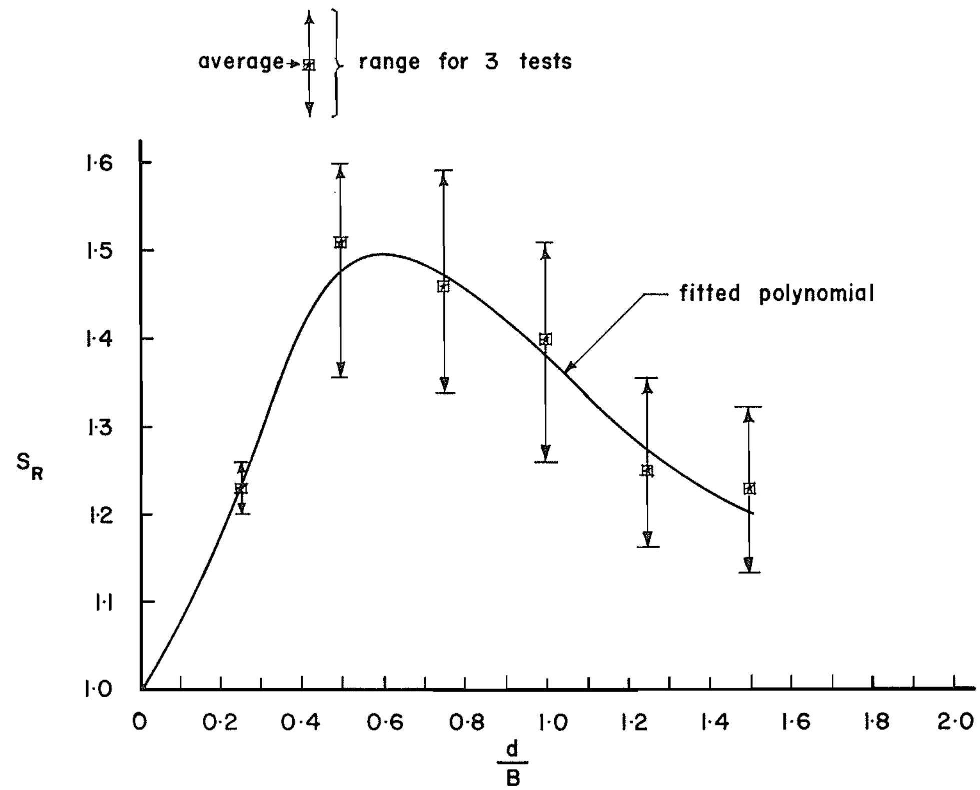

FIG. 6. Influence of the depth of location of the reinforcement on the initial stiffness of rigid footing located on sloped fill (S_R defined by [1]).

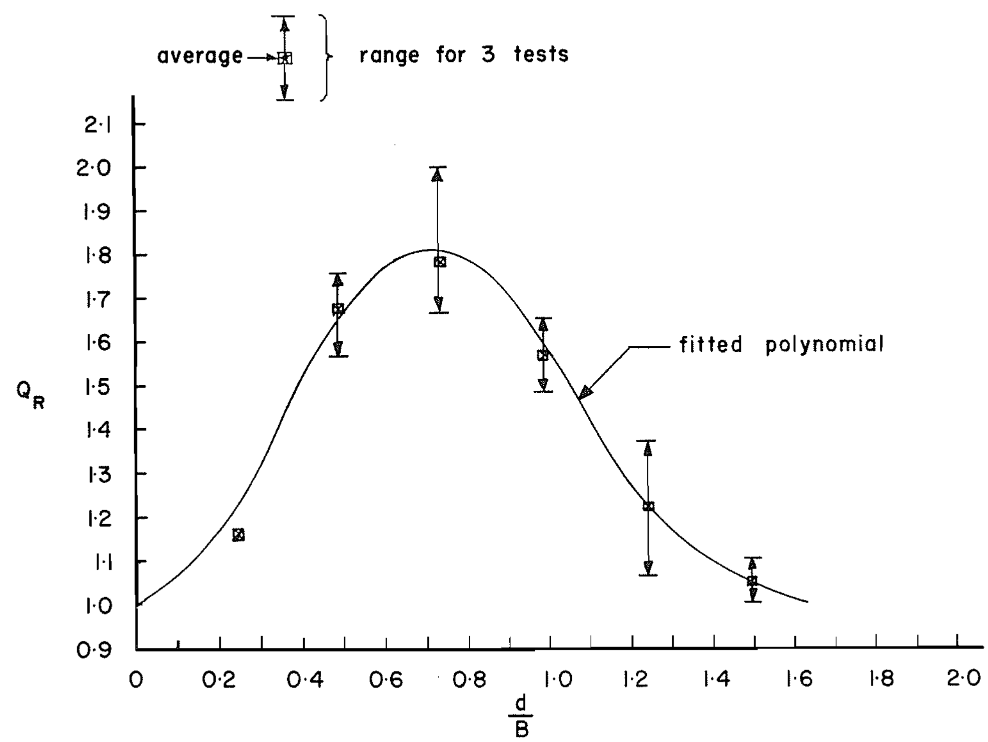

FIG. 7. Influence of the depth of location of the reinforcement on the ultimate load capacity of rigid footing located on sloped fill (Q_R defined by [2]).

finement due to the grid openings are not fully mobilized in enhancing the performance of the footing.

The preceding results pertained specifically to the situation where the geogrid used in the experimental programme corresponded to the SS2 type. The influence of the geogrid type on the performance of the footing on a reinforced slope can be assessed only by recourse to an all-encompassing programme of experimental research similar to that described

TABLE 1. Variation of the ultimate load-carrying capacity with the type of geogrid*

	Tensar type			
	SS0	SS1	SS2	AR1
Aperture size (in.)				
MD	1.12	1.14	1.06	2.0
CMD	1.36	1.48	1.57	2.8
Thickness (in.)				
Min.	0.002	0.03	0.05	0.06
Max.	0.7	0.10	0.16	0.185
Open area (nominal) (%)	75	74	77	79
Peak tensile strength (lbf/ft)				
MD	580	840	1 170	1 070
CMD	820	1 400	2 100	1 840
Tensile strength (2% strain) (lbf/ft)				
MD	160	280	370	300
CMD	200	400	600	590
Tensile strength (5% strain) (lbf/ft)				
MD	370	570	700	675
CMD	540	630	1 200	1 150
Initial tangent modulus (flb/ft)				
MD	15 000	30 000	45 000	38 000
CMD	25 000	49 000	74 000	55 000
$P_{ult}^{Reinforced}/P_{ult}^{Unreinforced}$ (d = 0.7B) (average)	1.38	1.39	1.80	1.48

NOTES: MD, machine direction (i.e., along the roll length); CMD, cross-machine direction (i.e., across-roll width).
*Values given are as published by the Tensar Corporation. 1 in. = 25.4 mm; 1 lbf/ft = 0.0146 kN/m.

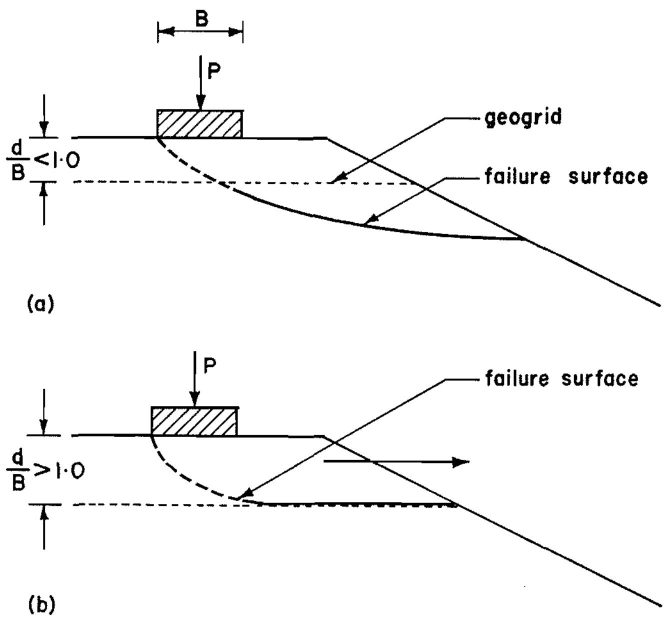

FIG. 8. Influence of the depth of location of the reinforcement on the development of failure planes within the soil mass: (*a*) "shallow" embedment of geogrid reinforcement; (*b*) "deep" embedment of geogrid reinforcement. (The solid portion of the failure surface is established experimentally; the dotted portion of the failure surface is developed by extrapolation and observation.)

previously. In this research programme, the influence of the geogrid type on the performance of the footing located on a slope is assessed by performing a restricted number of additional tests on other types of geogrids. In particular, attention is restricted to Tensar geogrid types SS0, SS1, and AR1. In the additional experiments, the depth of embedment of the geogrid is set at $d/B = 0.70$. This value of d/B approximately corresponds to the location at which the maximum ultimate load is observed for the foundation on a sloped soil that is reinforced by the Tensar SS2 geogrid. The location of failure paths derived from these additional tests involving Tensar geogrids SS0, SS1, and AR1 showed characteristics similar to those illustrated in Fig. 8. The results for the ultimate load capacity of the footing located on a sloped fill are summarized in Table 1. For ease of comparison, the various properties of the geogrids are also summarized in Table 1. These results suggest that the primary properties of geogrid that govern its effectiveness in increasing the load-carrying capacity of the sloped fill are the aperture size, modulus of elasticity, and tensile strength. Similar findings on other soil–geogrid–structure interaction problems support these observations (Tensar Corporation 1986).

Conclusions

Geogrids have been used in a variety of situations in geotechnical engineering where the soils need to be provided with additional resistance to deformation and failure. Such situations can arise in both temporary and permanent foundation systems involving both granular and cohesive soils. Apart from economic considerations, the continued use of geogrids in geotechnical applications will depend upon the extent to which the basic reinforcing mechanisms can be understood both in terms of analysis and experimentation in the laboratory and in field investigations. The present study focuses on the experimental investigation of the behaviour of a model footing on a reinforced sloped fill. Such footing configurations are used quite extensively as supports for bridge structures. An extensive review of the literature indicates that this category of soil-reinforcement problem has received virtually no attention. Consequently, prior to conducting large-scale field tests of such structures, it is instructive to establish, at least within the context of laboratory experimentation, the manner in which the reinforcement enhances the deformation and settlement behaviour of the footing located at the crest of a sloped reinforced fill. The small-scale laboratory experimentation primarily focuses on a single geogrid type and a single granular soil type; consequently, the results of the laboratory investigations are meant to be a qualitative indicator for the performance of footings on geogrid reinforcement in sloped fills.

The following conclusions can be used as a guide for assessing the performance of other types of full-scale investigations and geogrid types.

(i) The load-carrying capacity of a footing on a sloped fill structure can be improved in excess of 50% by incorporating geogrid reinforcement.

(ii) When considering the ultimate load-carrying capacity, the optimum location for the geogrid reinforcement occurs at a depth between 0.5 and 0.9 times the width of the foundation.

(iii) The increase in the ultimate load behaviour of the reinforced slope is achieved without sacrificing the ductility of the system. For example, the residual load-carrying capacity of the footing on a reinforced slope is always greater than the peak load for the footing on an unreinforced slope.

(iv) The initial stiffness of the footing can be increased in excess of 25% by incorporating a geogrid reinforcement layer at a depth between 0.5 and 0.9 times the width of the foundation.

(v) The primary properties of a geogrid that govern its effectiveness in improving the load-carrying capacity of the sloped fill are identified as the aperture size, the modulus of elasticity, and the tensile strength.

(vi) The location of the geogrid layer at a depth greater than twice the width of the footing does not lead to any improvement in either the load-carrying capacity or the stiffness characteristics of the footing on a sloped fill.

The results of the programme of experimental research are sufficiently encouraging to warrant their extension to prototype situations. Such extensions should incorporate not only variables such as the geogrid type and typical granular backfill used in bridge abutment situations but also the influence of quasi-static cyclic loads or dynamic loads.

Acknowledgements

The work described in this paper was supported in part by Natural Sciences and Engineering Research Council of Canada Grant A3866 awarded to the first author. The second author acknowledges the research support provided by the Faculty of Graduate Studies and Research at Carleton University. The authors are grateful to a referee for the valuable comments leading to improvement in the presentation of these research findings.

AKINMUSURU, J.O., and AKINBOLADE, J.A. 1981. Stability of loaded footings on reinforced soil. ASCE Journal of the Geotechnical Engineering Division, **107**: 819–827.

AKINMUSURU, J.O., AKINBOLADE, J.A., and ODIGIE, D.O. 1982. Bearing capacity tests on fibre-reinforced soil. Proceedings, 2nd International Conference on Geotextiles, Las Vegas, NV, pp. 599–603.

BASSETT, R.H., and LAST, N.C. 1978. Reinforcing earth below footings and embankments. Proceedings, ASCE Symposium on Reinforced Earth, Pittsburgh, PA, pp. 202–231.

BINQUET, J., and LEE, K.L. 1975*a*. Bearing capacity tests on reinforced earth slabs. ASCE Journal of the Geotechnical Engineering Division, **101**: 1241–1255.

______ 1975*b*. Bearing capacity analysis of reinforced earth slabs. ASCE Journal of the Geotechnical Engineering Divison, **101**: 1257–1276.

CHANG, D.K. 1985. Bearing capacity of shallow foundations reinforced with geogrids and geotextiles. M.Eng. thesis, The Cooper Union School of Engineering, New York, NY.

DEVATA, M.S. 1984. Geogrid reinforced earth embankments with steep side slopes. Proceedings, Conference on Polymer Grid Reinforcement, London, United Kingdom, pp. 82–87.

FRAGASZY, R.J., and LAWTON, E. 1984. Bearing capacity of reinforced sand subgrades. ASCE Journal of Geotechnical Engineering, **110**: 1500–1507.

GNANENDRAN, C.T. 1987. Footings on sloped fills: influence of a soil reinforcement layer. M.Eng. thesis, Carleton University, Ottawa, Ont.

INGOLD, T.S. 1982. Reinforced earth. Thomas Telford, London, United Kingdom.

JEWELL, R.A., MILLIGAN, G.W.E., SARSBY, R.W., and DUBOIS, D. 1984*a*. Interaction between soil and geogrids. Proceedings, Conference on Polymer Grid Reinforcement, London, United Kingdom, pp. 18–30.

JEWELL, R.A., PAINE, N., and WOODS, R.I. 1984*b*. Design methods for steep reinforced embankments. Proceedings, Conference on Polymer Grid Reinforcement, London, United Kingdom, pp. 70–81.

JONES, C.J.F.P. 1985. Earth reinforcement and soil structures. Butterworths Advanced Series in Geotechnical Engineering, London, United Kingdom.

KOERNER, R.M. 1986. Designing with geosynthetics. Prentice Hall, Englewood Cliffs, NJ.

MEYERHOF, G.G. 1963. Some recent research on the bearing capacity of foundations of slopes. Soils and Foundations, **1**: 30–37.

NETLON, LTD. 1982. Designing with tensar—techniques and design philosophy for utilizing tensar grids in the reinforcing of soil structures. Netlon Civil Engineering Department, Blackburn, United Kingdom.

SHIELDS, D.S., SCOTT, J.D., BAUER, G.E., DESCHENES, J.H., and BARSVARY, A.K. 1977. Bearing capacity of foundation near slopes. Proceedings, 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, vol. 2, pp. 715–720.

TENSAR CORPORATION. 1986. Slope reinforcement with tensar geogrids—design and construction guideline. Technical Note TTN:SRI-Mar.1986. Atlanta, GA.

WINTERKORN, H.F., and FANG, H.Y. 1975. Foundation engineering handbook. Van Nostrand Reinhold, New York, NY.