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Prediction of the behaviour of a geogrid reinforced sloped fill under footing load

C.T. Gnanendran
School of Civil Engineering, University College ADFA, University of New South Wales, Northcott Drive, Canberra, ACT 2600, Australia

ABSTRACT: This paper summarizes the results of a numerical study on the performance of a model footing located near the crest of a sloped fill reinforced with a layer of geogrid reinforcement. Predicting the load-settlement behaviour of the footing and the stabilising force contributed by the reinforcement proved difficult due to the effects of compaction during construction. The potential of modelling the compaction effects by varying the stiffness parameter K of the fill using both Janbu's and Duncan and Chang's models as well as using higher K_o value for setting the initial horizontal stresses are examined. The predicted behaviour of the reinforced sloped fill for these different scenarios are discussed in comparison to the measured responses. This study indicates that the load-settlement behaviour of the footing could be predicted well by adopting Janbu's equation for the stress dependent stiffness with high K values in the order of 4000 and $K_o = 1.0$ for setting the initial horizontal stresses. However, the tensile force in the reinforcement could not be predicted satisfactorily.

1 INTRODUCTION

Foundations located on sloped fills are used quite extensively as supports for bridge abutments and geosynthetic reinforcement are often used within the body of the fill to enhance its load carrying capacity and improve the load-settlement behaviour. Knowledge of the load carrying capacity of the reinforced sloped fill (or the load-settlement behaviour of foundations supported on it) and tensile forces/strains developed in the geosynthetic reinforcement are essential requirements for efficient design of these structures, however, predicting these responses had often been difficult.

The load settlement behaviour of a footing located near the crest of a sloped fill reinforced with a layer of geogrid reinforcement and the progressive development of stabilising force in the geogrid reinforcement with increasing footing load were studied until failure through a laboratory model (Fig. 1). The behaviour of this reinforced sloped fill under footing load was back analysed using an elasto-plastic, non-linear finite element model with the objective of predicting the load-settlement behaviour of the footing and the stabilising tensile force developed in the geogrid reinforcement. However, difficulties were encountered in predicting the load-settlement behaviour of the footing and the reinforcement strain/force development simultaneously from a single analysis apparently due to the effects of compaction. Different strategies were adopted for accounting the compaction effects by adopting different soil models and varying different model parameters. Details of the finite element numerical model and the predicted behaviour of the reinforced sloped fill under footing loading for different scenarios of model parameters to account the compaction effects and their relative merits are discussed in comparison to the measured performance of the footing and geogrid reinforcement.

2 BRIEF DESCRIPTION OF MODEL TESTING

A displacement controlled footing load test on a sloped fill reinforced with a layer of geogrid reinforcement was examined with an experimental setup shown in Fig. 1 (see Selvadurai and Gnanendran, 1989; and Gnanendran and Selvadurai, 2001 for further details). 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 was fitted with polished stainless steel sheets to minimize end effects and the bottom of the model strip footing was made rough by applying timber bonding glue and spraying Ottawa sand. Mortar sand (SP – poorly graded sand with effective diameter, D_{10} = 0.27 mm; coefficient of uniformity, C_u = 3.0; and the curvature coefficient, C_c = 0.95) was used as the fill material for model testing. The moisture content of the mortar sand was maintained between 4% and 5%. The bulk density of the mortar

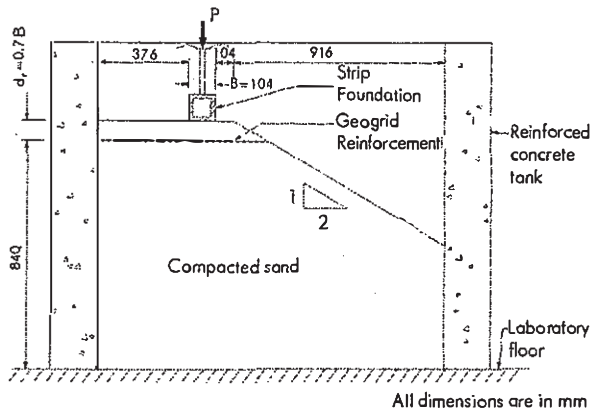

Figure 1. Configuration of the geogrid reinforced sloped fill (modified after Gnanendran and Selvadurai, 2001).

sand in its compacted state was kept constant at 17.6 kN/m^3 in all the experiments. Shear strength parameters of the soil were determined to be approximately c = 5 kPa and $\phi = 40°$.

An extruded polypropylene biaxial Tensar BX1200 (SS2) geogrid, measuring 870 mm wide by 740 mm long, instrumented with a number of strain gauges was used as reinforcement of the sloped fill. The depth of embedment of the geogrid reinforcement was selected to be d = 0.7B based on the studies reported by Selvadurai and Gnanendran (1989) which was expected to give the maximum improvement in the ultimate bearing capacity of the footing.

3 NUMERICAL MODELLING AND SELECTION OF PARAMETERS

To obtain reasonable stresses and strains in the sloped fill, it is necessary to consider both stress dependent stiffness characteristics of granular materials as well as plastic failure. Janbu's equation was used to account for the stress-dependent stiffness of the fill.

$$\frac{E}{P_a} = K\left[\frac{\sigma_3}{P_a}\right]^m \tag{1}$$

where E is the Young's modulus of the soil, P_a is the atmospheric pressure, σ_3 is the minor principal stress, and K and m are the empirical parameters. However, maximum and minimum E values of 25 and 2 MPa were assumed for the fill in all the analyses reported in this paper. Plastic failure of the fill was modelled using a Mohr-Coulomb failure criterion and a non-associated flow rule with a cohesion intercept c', friction angle ϕ' and dilatancy angle ψ. The properties of the fill material were obtained based on laboratory tests and the values used in the analyses were: γ = 17.6 kN/m^3, $c' = 5$, $\phi' = 40°$, $\psi = 9°$ and $\nu = 0.35$. K was varied for different analyses but m was assumed to be 0.5 for all the analyses reported in this paper.

The geotextile reinforcement was modelled as a series of linear elastic bar elements, whose axial stiffness (J) is a representative value per unit width of sloped fill. Based on wide-strip tensile tests, J = 450 kN/m for 0 – 2% strain, J = 600 kN/m for 0 – 1% strain, J = 700 kN/m for 0 – 0.5% strain and initial tangent stiffness = 1080 kN/m; and T_f = 32 kN/m (Mylleville, 1991). The reinforcement-soil interface was modelled using nodal compatibility joint elements, assumed to be rigid plastic and non-dilatant (i.e., $\psi = 0$). The geogrid-fill interface friction angle was taken to be 40°. Provision was made for slip between the reinforcement and the soil by incorporating interface slip elements above and below the reinforcement. Thus, slip could occur independently above and/or below the reinforcement. A modified version of the program AFENA (Carter and Balaam, 1995) was used for these analyses.

4 DETAILS OF ANALYSES

For the analyses of geosynthetic reinforced embankments on soft soils and retaining walls, modelling the granular fills using Janbu's stiffness parameter K ranging between about 500 and 1000 has been found to give reasonably good predictions (e.g., Rowe and Soderman, 1987; Rowe and Mylleville, 1989; Gnanendran and Rowe, 1995; and Ho and Rowe, 1996).

Consequently, two different analyses using K = 500 and 1000, hereafter referred as Runs 1 and 2 respectively, of the reinforced sloped fill under footing load were performed to study the load - settlement behaviour of the footing and the gradual develop-

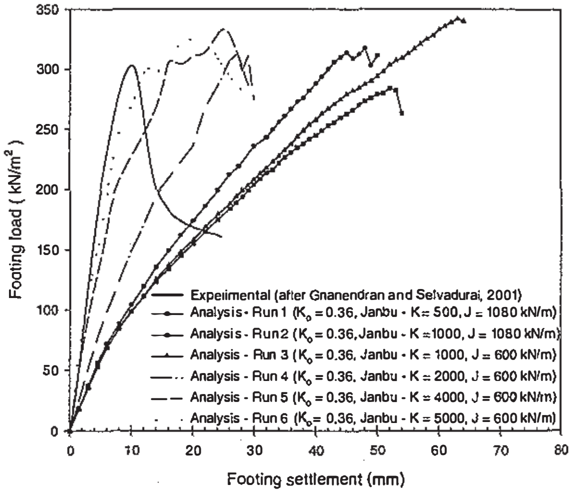

Figure 2. Variation of footing loading versus settlement for Runs 1 to 6 – comparison with experimental data.

ment of stabilising force in the reinforcement. Although, both these analyses predicted the ultimate load capacity of the reinforced sloped fill satisfactorily; the predicted load-settlement behaviour of the footing was found to be quite different from that measured in the laboratory (Fig. 2). Despite using the higher initial tangent stiffness of $J = 1080\ kN/m$ in both these analysis, the measured load-settlement response was much stiffer compared to that indicated by the analyses. However, to study the effect of using a more appropriate stiffness for the reinforcement, another analysis was performed with $J = 600\ kN/m$, i.e., stiffness corresponding to 0-1% strain, referred as Run 3.

4.1 *Effects of changing Janbu's K parameter*

The predicted load-settlement behaviour of the footing by all three analyses (i.e., Runs 1, 2 and 3) were different from the measured response and this difference is attributed primarily to the effects of compaction which was not considered in the numerical model. To verify whether the compaction effect could be modelled satisfactorily by changing the stiffness of the compacted fill, a series of analyses were carried out for increasing K values. Three analyses, hereafter referred as Runs 4, 5 and 6 corresponding to K = *2000, 4000* and *5000* respectively, were carried out in this series to model the effects of compaction on the stiffness of the soil. As evident from Fig. 2, the agreement between the predicted and measured footing load versus settlement behaviour improved with increasing K value. However, as will be discussed later, the comparison between the predicted and measured reinforcement force/strain worsened with increasing K value (see Fig. 3).

4.2 *Effects of changing K_o*

In all the analyses discussed above, the coefficient of earth pressure at rest, K_o, was considered to be according to Jaky's relationship of $K_o = 1\text{-}\sin \phi'$. However, compaction could induce higher initial horizontal stresses in the fill, prior to the application of footing load. To assess whether the influence of compaction could be accounted for approximately with higher initial horizontal stresses using a higher K_o value, two additional analyses were carried out with $K_o = 1$ for the cases of Janbu's stiffness parameter $K = 4000$ and $K = 5000$, referred as Runs 7 and 8 respectively (Fig. 4).

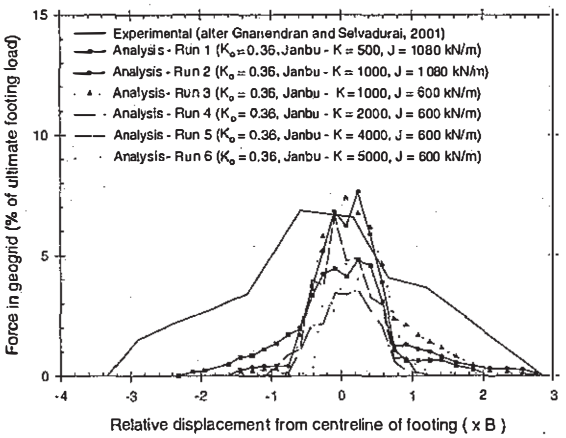

Figure 3. Variation of tensile force across the geogrid reinforcement for Runs 1 to 6 – comparison with experimental data.

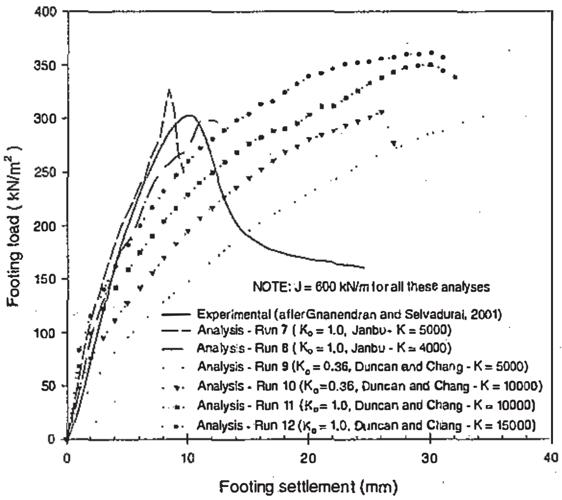

Figure 4. Variation of footing loading versus settlement for Runs 7 to 12 – comparison with experimental data.

4.3 *Influence of using Duncan and Chang Hyperbolic model*

Additional analyses were carried out to verify whether any other well-known soil model could yield better predictions for the behaviour of the reinforced sloped fill under footing loading and the Duncan and Chang (1970) hyperbolic model was chosen for this purpose. The tangential Young's modulus of the fill given by the following equation was used:

$$\frac{E}{P_a} = K\left[\frac{\sigma_3}{P_a}\right]^n [1-S] \qquad (2)$$

where,

$$S = \frac{r_f(1-\sin\phi)(\sigma_1-\sigma_3)}{2c\cos\phi + 2\sigma_3\sin\phi} \qquad (3)$$

K, n and r_f are non-dimensional constants. However, plastic failure of the soil was modelled using the Mohr-Coulomb criterion similar to the previous analyses.

Here again, the influence of increasing stiffness of the fill on the behaviour of the reinforced sloped fill under footing loading was investigated with K

values of 5000 and 10000 in Runs 9 and 10 respectively. However, n and r_f were assumed to be 0.5 and 0.8 for all the cases considered in this series. To examine the influence of using higher initial horizontal stresses with $K_o = 1$, two additional analyses, referred as Runs 11 and 12, were also performed for the cases of $K = 10000$ and 15000 respectively.

5 RESULTS AND DISCUSSION

The variation of footing load versus settlement predicted from Runs 1 to 6 are compared with the corresponding experimental data in Fig. 2. The predicted tensile force distribution across the geosynthetic reinforcement at ultimate footing load for each of these six analysis cases is compared with the measured response in Fig. 3. It can be observed from Figs. 2 and 3 that Run 2 with Janbu's $K = 500$ for the fill and reinforcement $J = 1080$ kN/m predicted the ultimate footing load satisfactorily (difference of only 5.6%) but under estimated the maximum reinforcement force at ultimate footing load by about 30%. When Janbu's K was increased to 1000 (i.e., Run 2), the analysis gave better predictions of both the ultimate footing load and maximum geogrid force at ultimate condition, i.e., under prediction of ultimate load by about 4.3% and over prediction of maximum geogrid force by about 11%. Although the reinforced soil system indicated a stiffer response in Run 2 compared to that of Run 1, the predicted footing load-settlement response was still significantly less stiff compared to that obtained in the experiments. This indicates that the predicted settlement at a given footing load would be much higher than the measured value (e.g., the predicted settlements at 250 kPa footing loading would be approximately 41 mm and 33 mm from Runs 1 and 2 whereas the measured settlement was only 7 mm).

For the analyses and design of reinforced soil structures it is common practice to use secant modulus rather than the initial tangent stiffness for the geosynthetic. Consequently, the secant stiffness of 600 kN/m corresponding to 0 to 1% strain was used in all the analyses reported in this paper except Runs 1 and 2. It is worth noting that the measured geogrid strains were less than 1% in the experiments (Gnanendran and Selvadurai, 2001) and the stiffness corresponding to 0 to 1% strain range is therefore appropriate for use in the analyses.

With Janbu's $K = 1000$ for the fill, decrease of the geogrid stiffness from $J = 1080$ in Run 2 to 600 kN/m in Run 3 resulted in a decrease in the overall stiffness of the reinforced soil system as expected. Run 3 over predicted the ultimate footing load by about 13.6% but the maximum reinforcement force at ultimate footing load was reasonably well predicted. However, the maximum footing load predicted in Run 3 was at a significantly larger settlement compared to those of both Runs 1 and 2 and at much higher settlement than that observed in the experiment.

Despite the fact that the value of Janbu's K commonly used for analysing reinforced soil structures range between 500 and 1000, all the three analyses (i.e., Runs 1 to 3) failed to predict the measured load-settlement and geogrid strain responses satisfactorily. This is attributed to the effects of compaction on the stress-strain characteristics of the reinforced soil system. To model the compaction effects approximately, higher Janbu's K values of 2000, 4000 and 5000 were attempted for modelling the fill material behaviour in Runs 4, 5 and 6.

The use of higher K values resulted in improved prediction of the load-settlement behaviour of the footing (Fig. 2), the use of K = 5000 in Run 6 giving the best load settlement response followed by that of Run 5 and subsequently that of Run 4. However, the geogrid strain distribution at ultimate footing load predicted by the analyses deviated further from the measured response, the maximum reinforcement force was under predicted by as high as 48% in Run 6. It is therefore apparent that the compaction effects could not be modelled satisfactorily by adopting higher values for Janbu's stiffness parameter K for the fill material.

Compaction could induce higher initial horizontal stresses than that usually estimated assuming geostatic K_o ($\simeq 1\text{-}\sin\phi'$) condition. This is more likely to be the situation in laboratory model tests where rigid boundaries are used in the experimental set up compared to field conditions. To verify whether the compaction effects could be modelled satisfactorily with the combination of higher stiffness for the fill (i.e., higher values for the Janbu's stiffness constant K) and higher K_o value for setting up the initial horizontal stresses, two additional analyses were performed. In both these analyses, i.e., Runs 7 and 8, K_o was assumed to be 1.0 but Janbu's stiffness parameter was assumed to be $K = 4000$ and 5000 respectively for the two analyses.

The footing load versus settlement behaviour predicted from the two analyses had closer agreement with the experimental results than the analyses discussed previously (i.e., Runs 1 to 6 - see Figs. 4 and 2). However, the maximum reinforcement force at ultimate footing load was under predicted by 74% and 46% in Runs 7 and 8. This indicates that the predicted reinforcement forces from Runs 7 and 8 are lower than those obtained for the corresponding analyses Runs 5 and 6 where the usual geostatic K_o ($\simeq 1\text{-}\sin\phi'$) value was assumed (Figs. 5 and 3) for setting the initial horizontal stresses.

Of all the analyses cases considered so far, Run 8 with $K_o = 1.0$ and Janbu's $K = 4000$ appears to give the best prediction of the load settlement response and tensile force distribution across the reinforcement. This analysis gave correct prediction of the ultimate footing load, indicated a load-settlement response closer to that obtained from the experiment but under predicted the maximum reinforcement force by about 46%.

The tensile force distribution across the reinforcement predicted by different analyses indicate a more localised reinforcing effect close to the footing even for cases where the maximum tensile force was well predicted (e.g., Run 3) whereas the experiment indicated a fairly spread distribution (Figs. 3 and 5). This observation suggests that an additional factor such as the occurrence of reinforcement pre-tensioning during compaction and/or the reinforcement stiffness increasing with vertical (or confining) stress need to be considered for predicting all the responses accurately from a single analysis. However, these have to be verified experimentally prior to use in the analysis and are beyond the scope of this paper.

Analyses using the Duncan and Chang hyperbolic model for the fill material with $K = 5000$ and 10000, but with the usual geostatic $K_o\ (\approx 1\text{-}sin\ \phi')$ for setting the initial horizontal stresses, also predicted the ultimate footing load accurately (the difference being less than 2% compared to the experimental data for both Runs 9 and 10). The predicted load-settlement responses were quite different from the experimental data, the ultimate (maximum) loads occurring at significantly larger settlements but the prediction improving with increasing K value from 5000 in Run 9 to 10000 in Run 10. Here again the predicted tensile force across the reinforcement at ultimate footing load was much lower than the measured value; the difference of the maximum force being 56 and 51% respectively for Runs 9 and 10 respectively compared to the experimental data.

When K_o was increased to 1.0 in Run 11 to account for higher initial horizontal stresses induced by compaction, the ultimate footing load was over predicted by about 17% and the predicted load-settlement behaviour of the footing showed a stiffer response but still significantly different from the experimental result (Fig. 4). The ultimate footing load was over predicted by about 20% when the Duncan and Chang stiffness parameter K was increased further to 15000 in Run 12. However, the load - settlement response predicted from Run 12 agreed better with the experimental data for smaller settlements compared to that of Run 11 and it indicated a relatively plastic type response afterwards whereas the experimental data indicated a strain softening type of behaviour. The predicted settlements at a typical footing loading of, say, 250 kPa were approximately 9, 12 and 15.5 mm from Runs 12, 11 and 10 while the measured settlement was 7 mm. However, the maximum footing loads occurred at a significantly higher settlement of about 30 mm in Runs 11 and 12 and hence the predicted tensile force distributions across the reinforcement at ultimate footing load were relatively better than Runs 7 to 10 analyses (see Fig. 5).

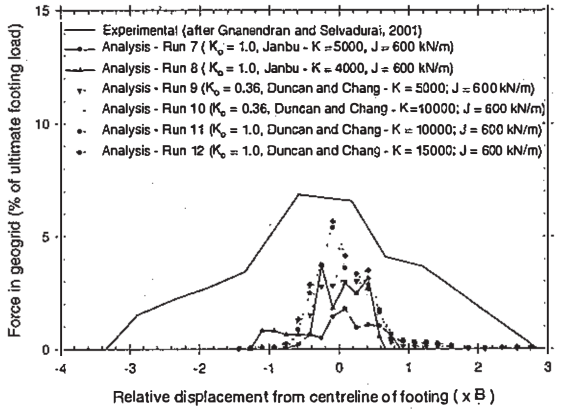

Figure 5. Variation of tensile force across the geogrid reinforcement for Runs 7 to 12 – comparison with experimental data.

Runs 11 and 12 under predicted the maximum tensile force in the reinforcement at ultimate footing load by 21 and 17% respectively compared to 46% in Run 8. For the load-settlement behaviour of the footing, Run 8 gave the best prediction and it accurately predicted the ultimate footing load. But it under estimated the reinforcement force significantly.

In summary, this study indicates that the behaviour of the geogrid reinforced sloped fill subjected to footing loading could be predicted well by adopting Janbu's equation for the stress dependent stiffness with high K values in the order of 4000 and $K_o = 1.0$ for setting the initial horizontal stresses. However, the tensile force in the reinforcement could not be predicted satisfactorily and it is believed that other factors such as the development of pretensioning force during compaction and/or stress dependent stiffness for the reinforcement need to be considered to improve the prediction. Duncan and Chang hyperbolic model with higher stiffness constant in the order of 10000 to 15000 and $K_o = 1.0$ gave relatively better prediction than the other cases for the reinforcement force but still couldn't predict the load settlement behaviour of the footing at higher footing loading close to ultimate and the reinforcement force satisfactorily from a single analysis.

6 SUMMARY AND CONCLUSION

The load-settlement behaviour of a footing located near the crest of a sloped fill reinforced with a layer of geogrid reinforcement and the stabilising force contributed progressively by the geogrid reinforcement were studied until failure of the footing through a laboratory model. An elasto-plastic non-linear finite element model was used to analyse this problem with the objective of predicting the load-settlement behaviour of the footing and the stabilising tensile force developed in the geogrid reinforcement. The stress dependent stiffness characteristic of the fill was modeled using Janbu's equation. Details of the model and the parameters selected for analyses are discussed in the paper.

Difficulties were encountered for predicting the load-settlement behaviour of the footing and the reinforcement strain/force simultaneously from a single analysis apparently due to the effects of compaction. Different strategies such as varying Janbu's stiffness parameter K of the fill, using a higher K_o value for setting the initial horizontal stresses in the fill and adopting Duncan and Chang hyperbolic model for the fill were attempted for considering the compaction effects. The predicted behaviour of the reinforced sloped fill under footing loading for these different scenarios of model parameters are discussed in comparison to the measured load-settlement behaviour of the footing and the tensile force developed in the geogrid reinforcement.

This numerical investigation indicates that the load-settlement behaviour of the geogrid reinforced sloped fill subjected to footing loading could be predicted well by adopting Janbu's equation for the stress dependent stiffness with high K values of the order of 4000 and $K_o = 1.0$ for setting the initial horizontal stresses. However, the tensile force in the reinforcement could not be predicted satisfactorily and it is believed that other factors such as the development of pretensioning force during compaction also need to be incorporated. Analysis using Duncan and Chang hyperbolic model with higher stiffness constant K in the order of 10000 to 15000 coupled with $K_o = 1.0$ predicted the load-settlement behaviour of the footing satisfactorily under typical working stress conditions. However, the ultimate footing load, load-settlement behaviour at higher loading condition closer to the ultimate and the reinforcement force couldn't be predicted satisfactorily using this approach.

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